GREEN Forum

Hosted by NASA Glenn Research Center

July 2, 2009: 1:00 – 2:30

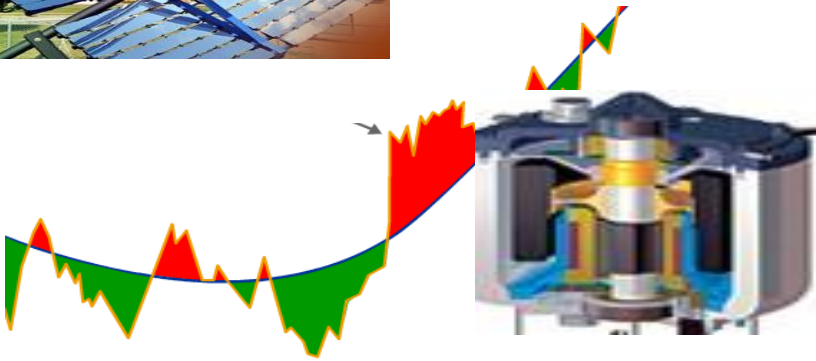
Administration Building Auditorium

Flywheels: A Key Technology for Renewable Energy Storage

Jeff Trudell and Raymond Beach

NASA Glenn Research Center

Intermittent energy sources such as solar and wind can use the power grid to absorb production, which relies on the load following capability of the traditional generating units. At low penetration levels, this works fine as the grid has already handled a similar variability in electricity demand. At high penetration levels, grid energy storage becomes necessary.   Flywheels can store and release kinetic energy quickly upon demand over many charge-discharge cycles to provide frequency regulation support instead of trying to constantly adjust generator output.   Technology development over the past decade have enabled flywheels to become a commercial product with many possible uses including trains, cranes, uninterruptible power supplies, pulse power, as well as frequency regulation.   With the aid of new technology to lower costs and increase stored energy, flywheels will play a significant role in securing global energy sustainability.   The presentation will explore flywheel technology for renewable energy storage, discuss flywheel design and safety considerations, present NASA flywheel programs and applications, and summarize future technology development needs.



Come join us as we continue to explore what could lie ahead for our country and our world in advanced renewable energy!

Agenda

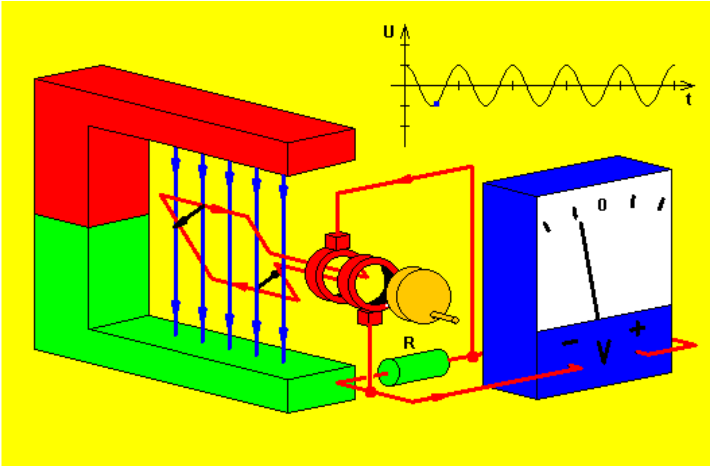
- What is a flywheel and NASA Glenn’s Role?
- Why is a renewable energy supply needed?
- Are flywheels a key technology for renewable energy?
- State of the current commercial technology
- State of NASA technology
- Future research directions
- Summary

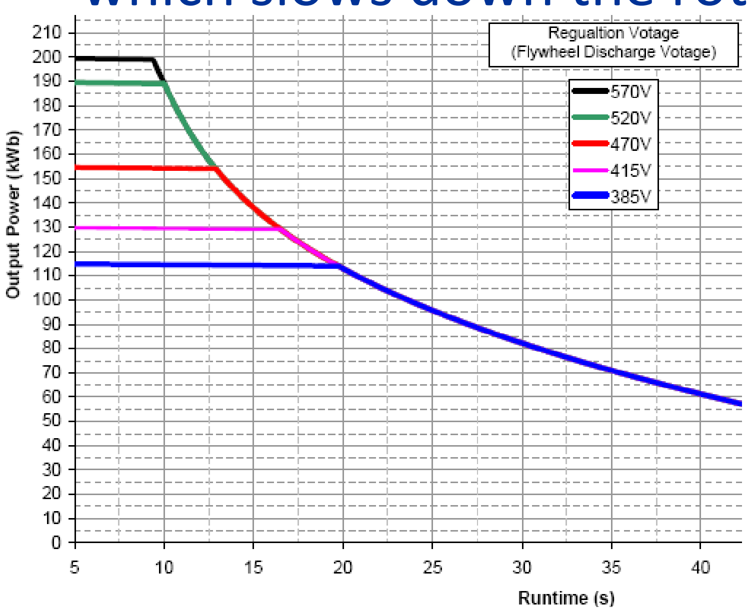
What is a flywheel?
What are the benefits or advantages?

Flywheels Store Kinetic Energy

- **ENERGY = ½ I_p ω²** I_p Ξ Moment of Inertia ≈ mass * r²
- A flywheel stores energy mechanically by spinning a high inertia mass. Energy is stored by increasing the speed of the rotor with the motor. Energy is supplied by the generator, which slows down the rotor.

ω = angular velocity

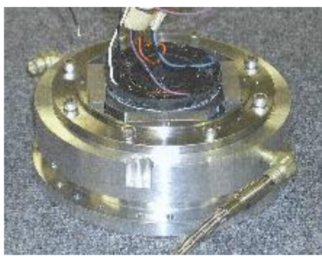




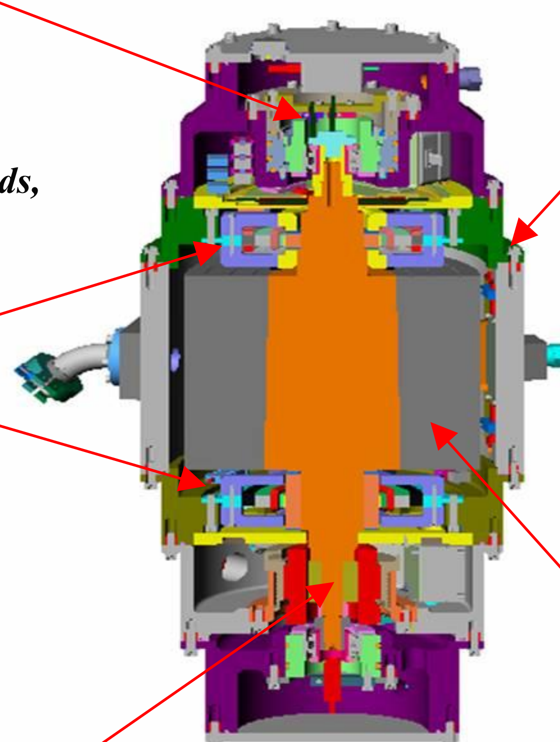
Faraday's Law: The principle states that when an electric conductor, such as a copper wire, is moved through a magnetic field, electric current will flow through the conductor.

Flywheel Technology – G2

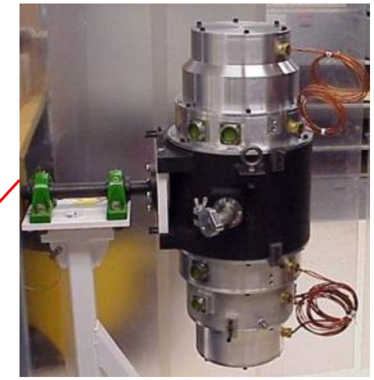
Auxiliary Bearings – touchdown and launch loads, stability, caging



Magnetic Bearings – low losses, higher speeds, sensors, dynamic control



Motor/Generator – low losses, higher speeds, drive controls



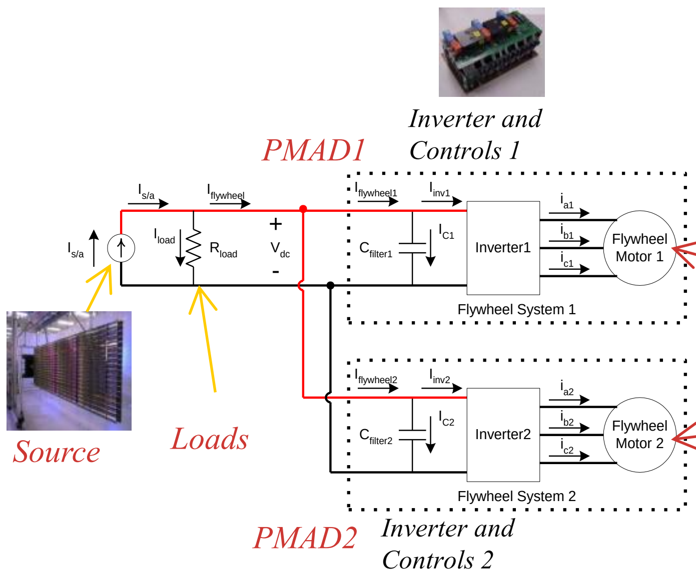
Housing – system and component integration, structural/dynamic response

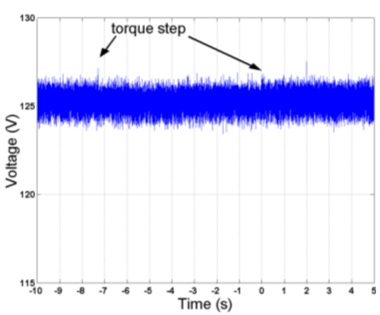
Composite Rotor – long life, safety without containment, light-weight hubs, design and cert. standards

Flywheel Advantages

- Long life of 15 years
- High combined specific energy and power
- Large Temperature Range (-45ºC to +50ºC), minor performance impacts with increasing range, cold soak ok
- Known state of charge
- Fault Tolerant
- Built in diagnostics for health monitoring
- Can easily provide 10 times peaking power capability
- Fault Isolation can eliminate electronics (a motor and generator can isolate faults
- Eliminates (most of) Attitude Control System on LEO satellites

Integrated Power and Attitude Control
D1 and G2 Test Demonstration at GRC





DC bus voltage

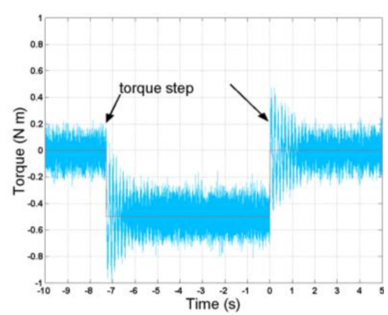
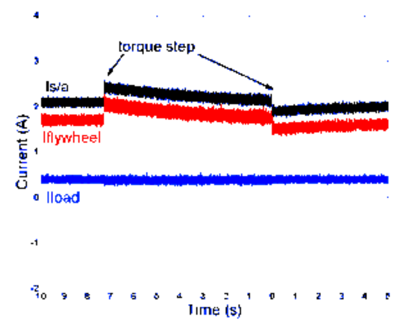
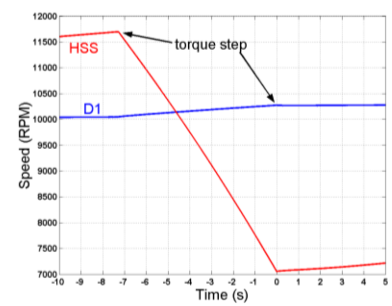


Table torque



DC Currents

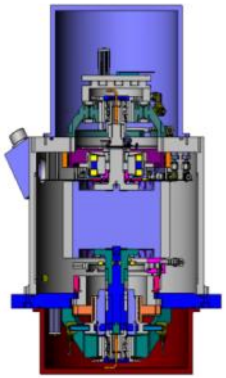


Flywheel speeds

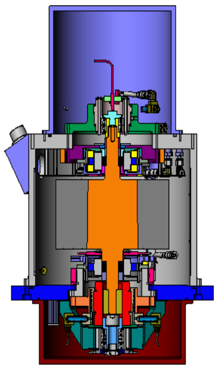
Charge mode with a step change in torque command

Aerospace Flywheel Modules at NASA Glenn

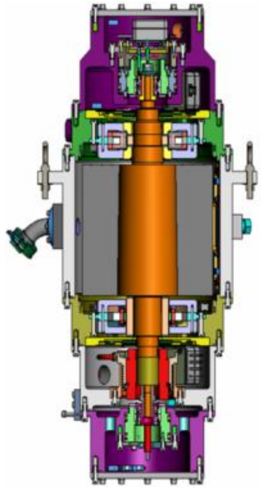
EVOLUTION!!!!!!



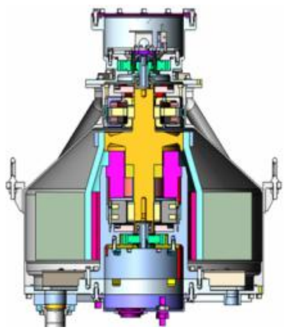
Dev 1 - 300 W-hr
4.1 W-hr/kg
Full Speed Once
USFS



D1 - 330 W-hr
4.7 W-hr/kg
Full Speed Many Times
GRC/TAMU/USFS



G2 - 581 W-hr
6.1 W-hr/kg
Modular, Low Cost
GRC/TAMU



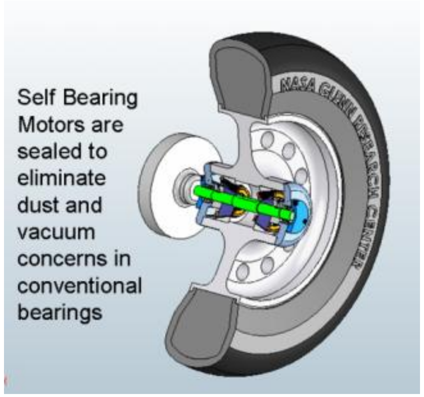
G3 - **2136** W-hr
35.5 W-hr/kg
High Energy, S.E., Life
GRC/TAMU/UT-CEM

GRC Flywheel Papers

- G2 Flywheel Module Design http://gltrs.grc.nasa.gov/reports/2006/CR-2006-213862.pdf
- Experimental Performance Evaluation of a High Speed Permanent Magnet Synchronous Motor and Drive for a Flywheel Application at Different Frequencies http://gltrs.grc.nasa.gov/Citations.aspx?id=2287
- Stabilizing Gyroscopic Modes in Magnetic-Bearing-Supported Flywheels by Using Cross-Axis Proportional Gains http://gltrs.grc.nasa.gov/Citations.aspx?id=246
- Stability Limits of a PD Controller for a Flywheel Supported on Rigid Rotor and Magnetic Bearings http://gltrs.grc.nasa.gov/Citations.aspx?id=238
- Modeling and Development of a Magnetic Bearing Controller for a High Speed flywheel System http://gltrs.grc.nasa.gov/Citations.aspx?id=788
- Demonstration of Attitude Control and Bus Regulation With flywheels http://gltrs.grc.nasa.gov/Citations.aspx?id=782
- Inverter Output Filter Effect on PWM Motor Drives of a flywheel Energy Storage System http://gltrs.grc.nasa.gov/Citations.aspx?id=1328
- Demonstration of Single Axis Combined Attitude Control and Energy Storage Using Two Flywheels http://gltrs.grc.nasa.gov/Citations.aspx?id=1199
- Time-Temperature Dependent Response of Filament Wound Composites for flywheel Rotors http://gltrs.grc.nasa.gov/Citations.aspx?id=1139
- PWM Switching Frequency Effects on Eddy Current Sensors for Magnetically Suspended flywheel Systems http://gltrs.grc.nasa.gov/Citations.aspx?id=689
- Magnetic Bearing Controller Improvements for High Speed flywhe**el** System http://gltrs.grc.nasa.gov/Citations.aspx?id=730
- A Study of Time-Dependent and Anisotropic Effects on the Deformation Response of Two flywheel Designs http://gltrs.grc.nasa.gov/Citations.aspx?id=884
- Ultrasonic Resonance Spectroscopy of Composite Rims for flywheel Rotors http://gltrs.grc.nasa.gov/Citations.aspx?id=1722
- Redesign of Glenn Research Center D1 Flywheel Module http://gltrs.grc.nasa.gov/Citations.aspx?id=1460
- At least a dozen other papers

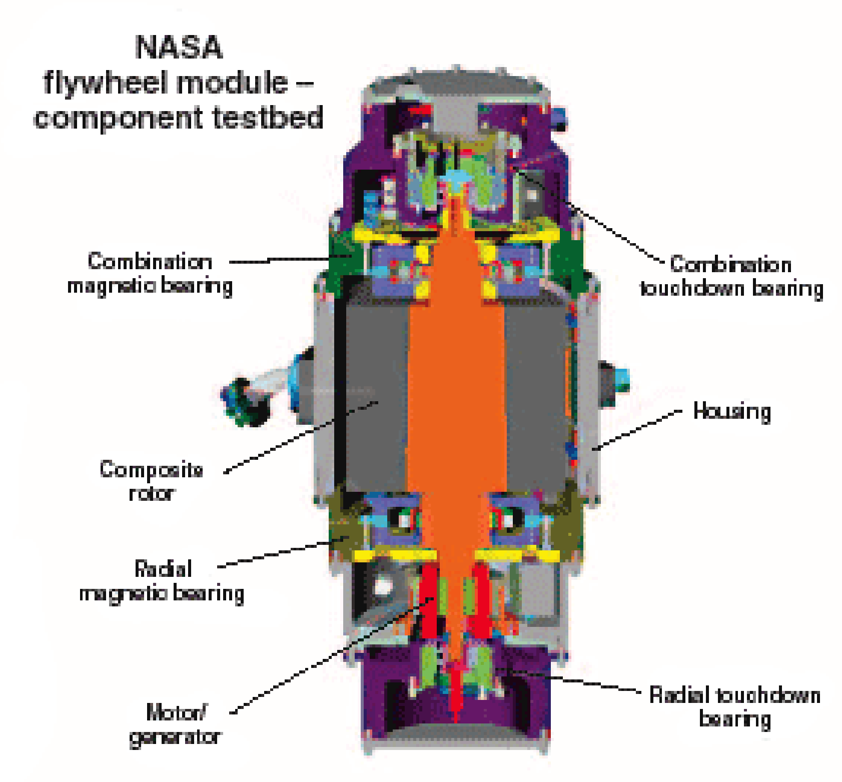
How much flywheel development costs

- NASA (40M, 8 years)
  - Lab demo of integrated energy storage and attitude control with two magnetically levitated 60,000 RPM carbon fiber flywheels
- Corporate (35M, 8 years)
  - Beta flywheel UPS, 60,000 RPM carbon fiber, magnetically levitated flywheel
- NASA (3M, 2 years)
  - Design and checkout of one carbon fiber, magnetically levitated, 60,000 RPM flywheel
- NASA (300K, 1 year)
  - Design and demonstration of 1000 RPM bearingless motor



Why flywheels are a fun engineering project.

- Multidiscipline project with many leading edge technologies
  - Materials (energy density)
    - Carbon fiber
    - Advanced fibers
  - Electrical Engineering (power density)
    - Motor design
    - Magnetic bearing design
    - Power electronics
    - Controls
  - Mechanical Engineering (practicality)
    - Rotordynamics
    - Vacuum systems
    - Thermal, Stress
  - System and Aero Engineering



Thanks!

GRC Flywheel Team
Academic and Industry Partners
Flywheel Developers over the decades

WHY IS A RENEWABLE ENERGY SUPPLY NEEDED?

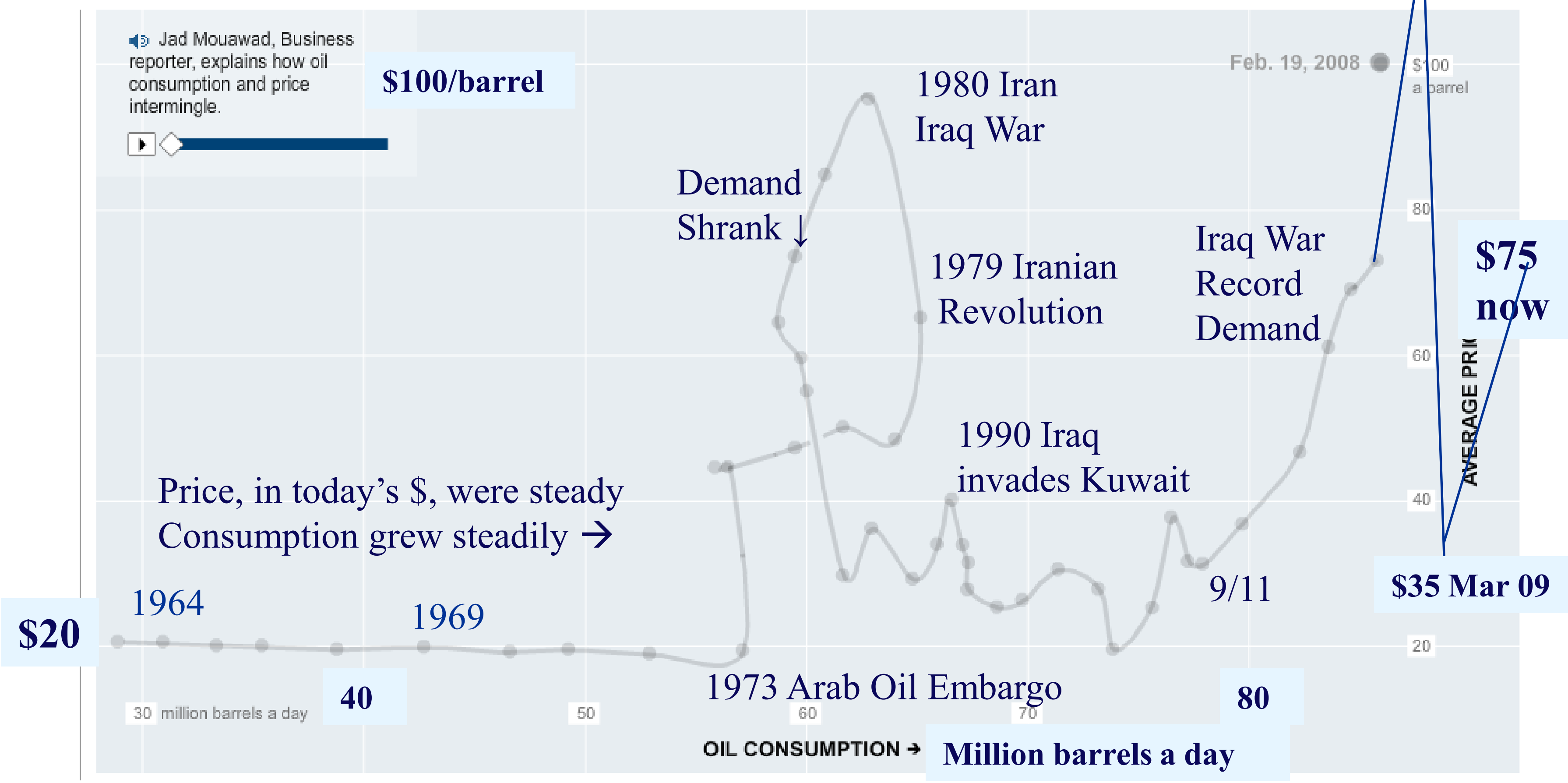
-Current Oil and Coal Supply versus Demand

-Cost of Current Energy Sources

-Environment

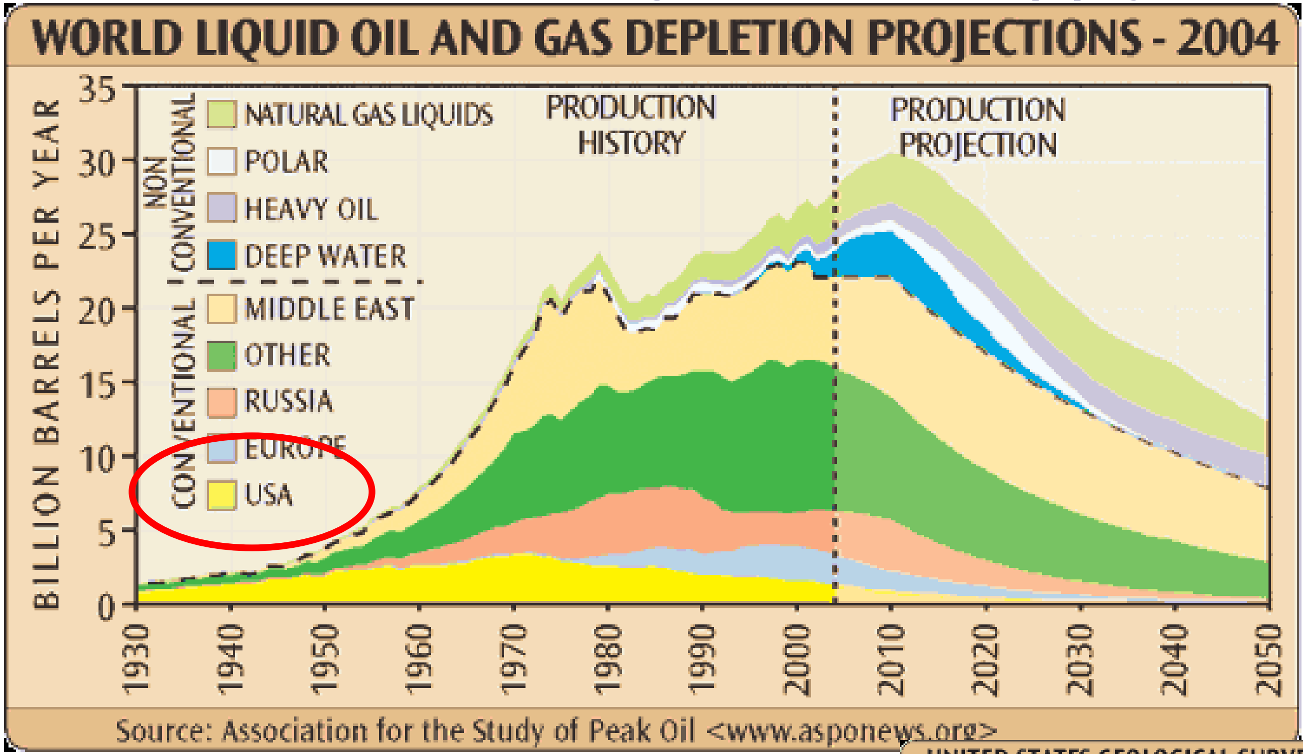
Cost Per Barrel vs Oil Consumption 1960-2008

US imports 14 of the 21 million barrels of oil used per day
US uses 5B barrels/year – at $100/barrel = $500B exported per year
http://www.washingtontimes.com/news/2009/may/19/countries-rated-on-oil-security/print/

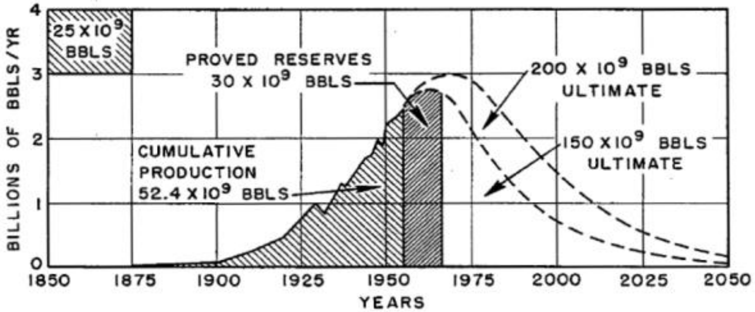


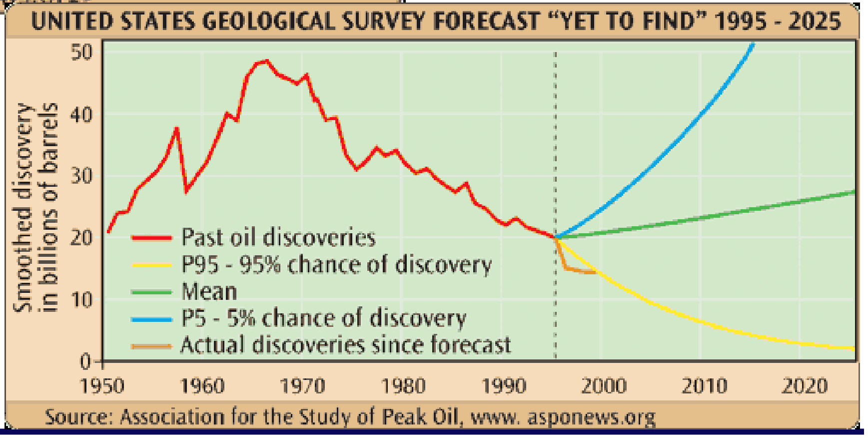
http://www.nytimes.com/interactive/2008/02/19/business/20080220_CENTURY_GRAPHIC.html

How long will Oil Supply Last?

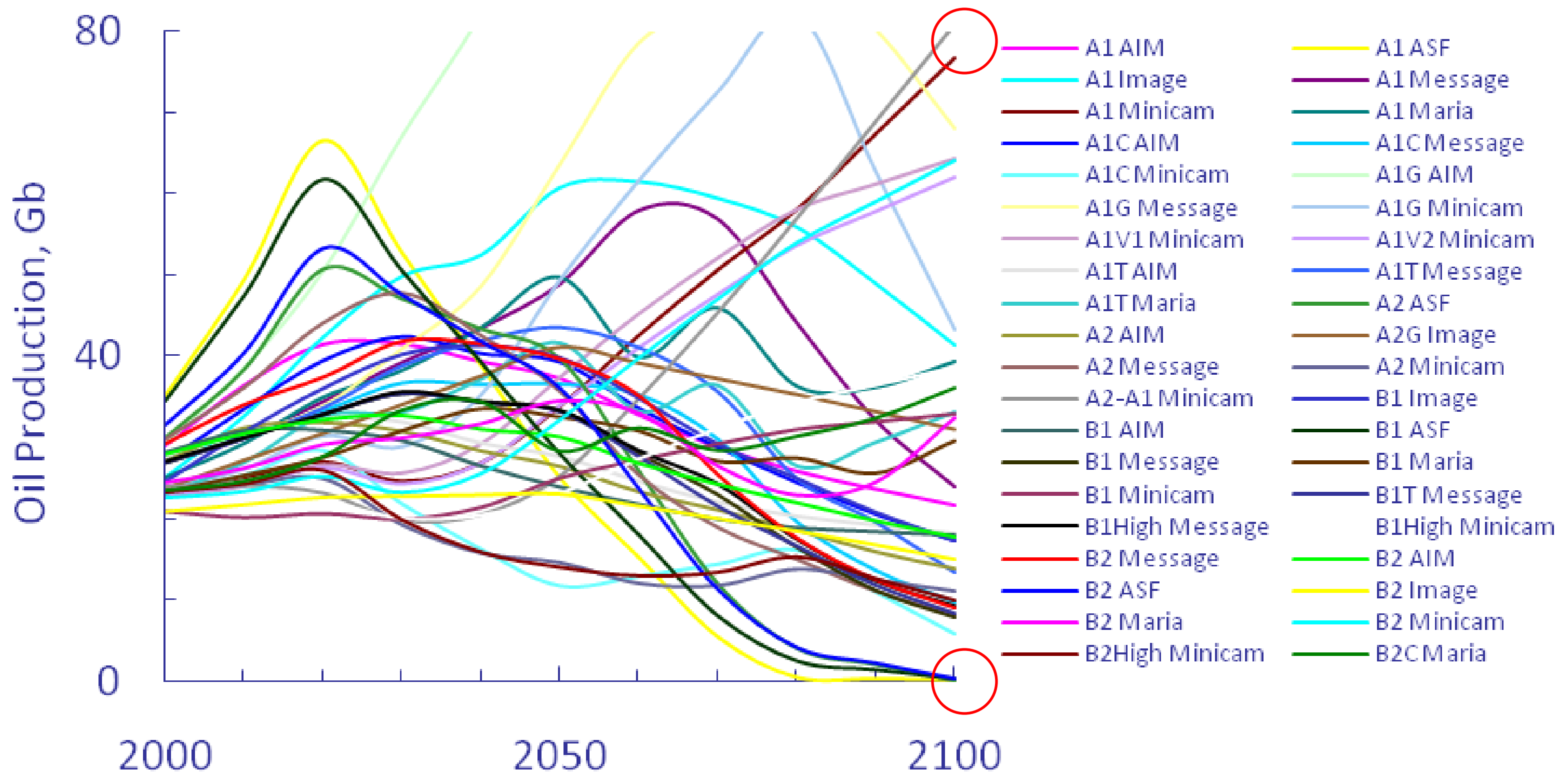


Similar to Hubbert's Peak - 1956





Oil Production in the IPCC Scenarios



- Gb = billions of barrels , 1 barrel = 42 gallons = 159 liters
- Ratio of total oil production from largest to smallest is 5:1
- From the IPCC: "… 40 SRES scenarios together encompass the current range of uncertainties"
- In some scenarios, production is rising in 2100 — implied ratio is 10:1
- This large ratio dominates the uncertainty in climate simulations — IPCC *likely* range for sensitivity is 2.0 to 4.5°C for a CO_2 doubling

Peak oil projections from Chevron's CTO

- “The ‘geological endowment’ of conventional oil--that is, the amount of oil in the Earth--once totaled about **3 trillion barrels**”
- We've used about **1.1 trillion**.
- Oil companies with current technologies can't get it all out of the ground, so maybe there is **a trillion barrels left** for human consumption.
- http://news.cnet.com/8301-10784_3-9803819-7.html, Oct 2007

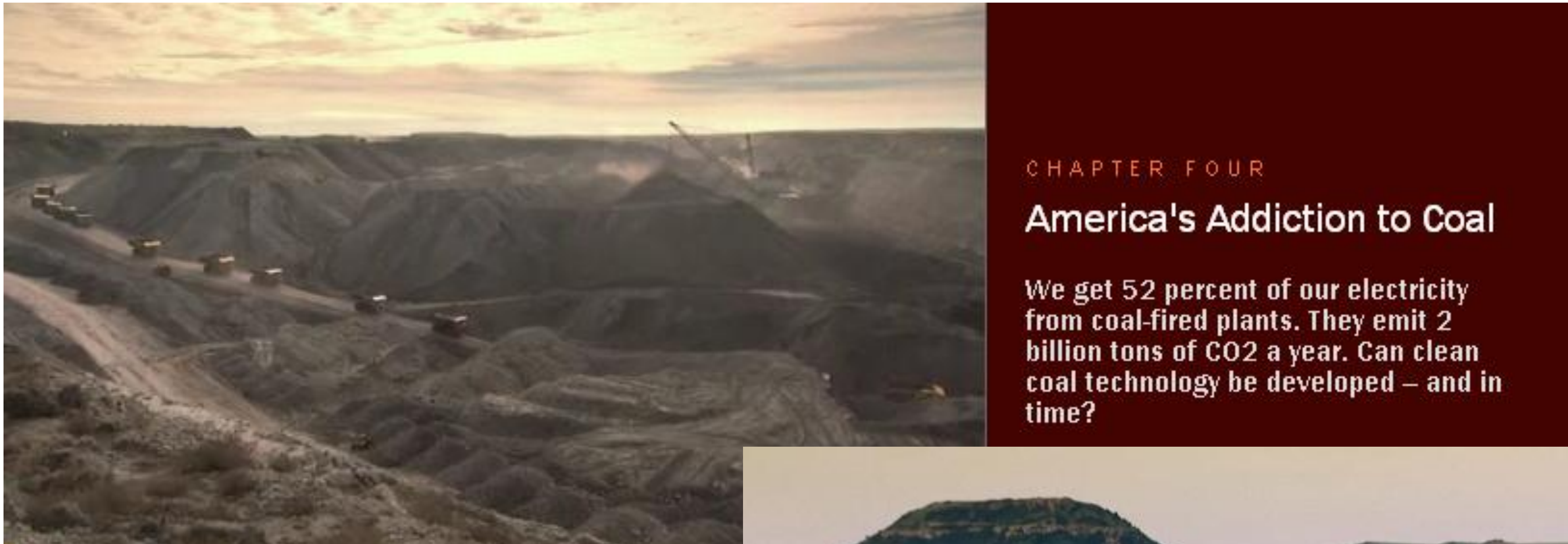
- 1 Trillion barrels / (83M bpd*365 days) = **33 years**
- If its 2 Trillion barrels its is = **66 years**.
- Must consider usage and supply:
  - http://www.youtube.com/watch?v=F-QA2rkpBSY

Other Consumption Sources

- http://www.eia.doe.gov/basics/quickoil.html
- World
- Total World Oil Production (2006) 82,433,000 *barrels/day*
- Total World Petroleum Consumption (2006) 84,979,000 *barrels/day*

- http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/company_level_imports/current/import.html
- Monthly data on the origins of crude oil imports in March 2009 has been released and it shows that two countries exported more than 1.00 million barrels per day to the United States (see table below). The top five exporting countries accounted for 62 percent of United States crude oil imports in March while the top ten sources accounted for approximately 84 percent of all U.S. crude oil imports. The top sources of US crude oil imports for March were Canada (1.845 million barrels per day), Mexico (1.092 million barrels per day), Venezuela (.949 million barrels per day), Saudi Arabia (0.944 million barrels per day), and Nigeria (0.860 million barrels per day). The rest of the top ten sources, in order, were Angola (0.644 million barrels per day), Iraq (0.587 million barrels per day), Brazil (0.334 million barrels per day), Columbia (0.254 million barrels per day), and Russia (0.219 million barrels per day). Total crude oil imports averaged 9.219 million barrels per day in March, which is an increase of (0.014) million barrels per day from February 2009.

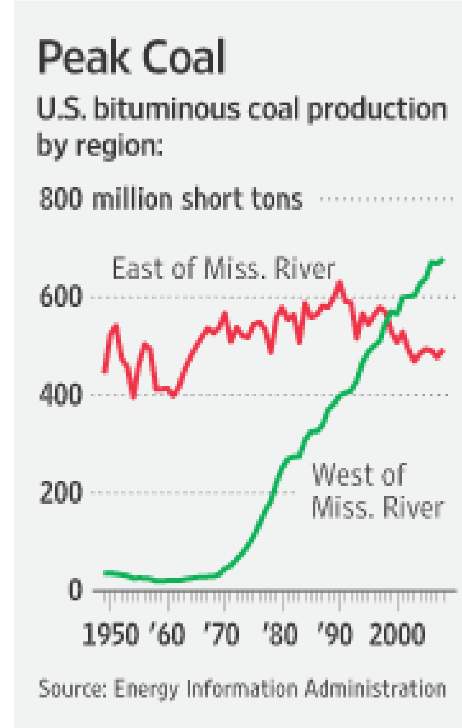
Coal – base load power



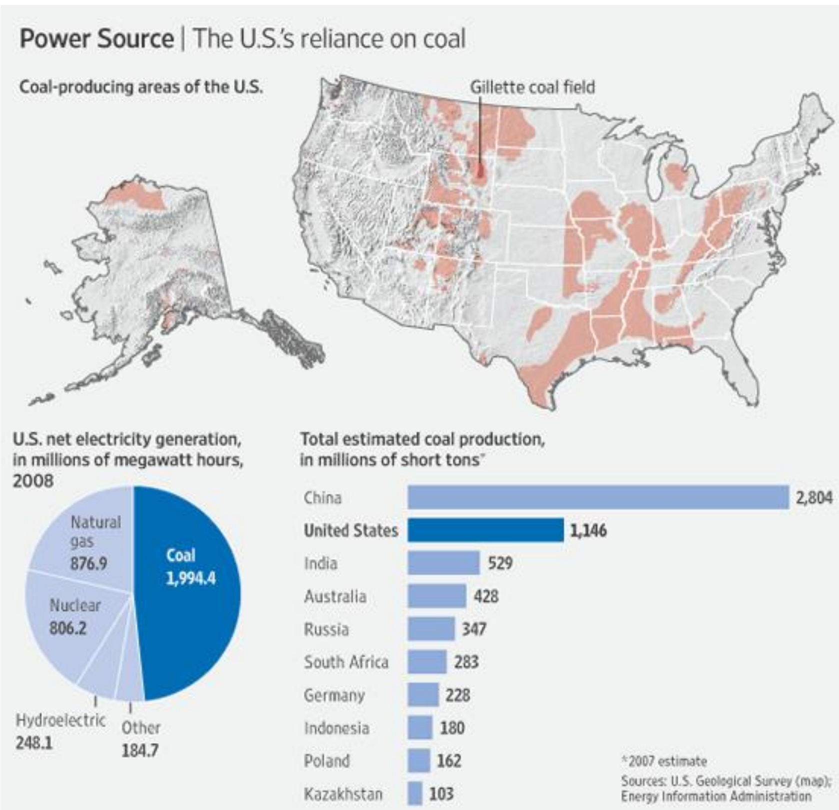
In the Wyoming Powder River Basin, they shovel 1M tons/day – 35 miles of Union Pacific trains/day

PBS “Heat” Watch Online: http://www.pbs.org/wgbh/pages/frontline/heat/

Wall Street Journal, June 8, 2009, Rebbeca Smith



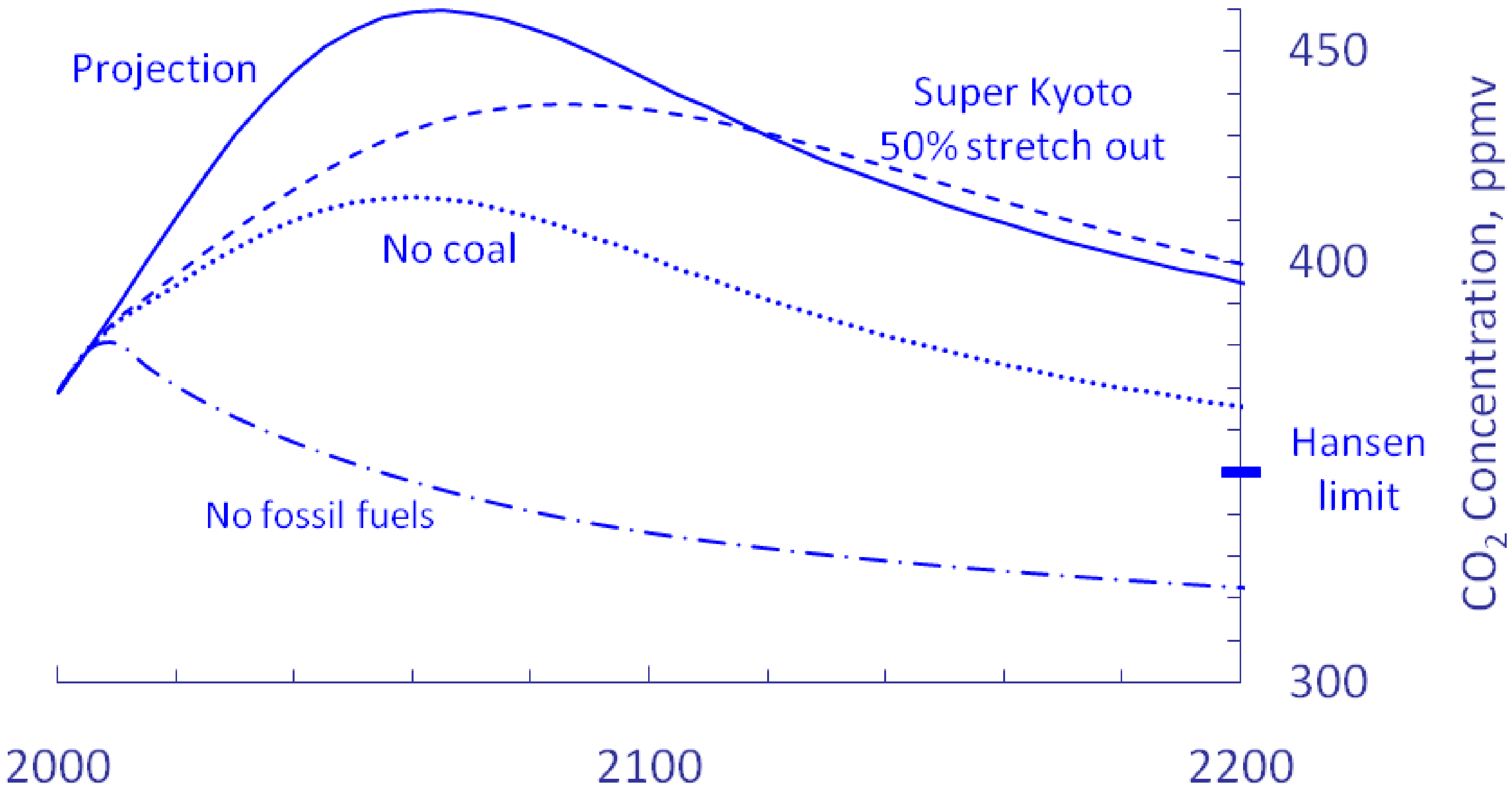
Last year, the U.S. Geological Survey completed an extensive analysis of Wyoming's Gillette coal field, the nation's largest and most productive, and determined that **less than 6% of the coal in its biggest beds could be mined profitably, even at prices higher than today's**.



Mining companies report they have to dig deeper and move more earth to extract coal from aging mines, driving up costs.

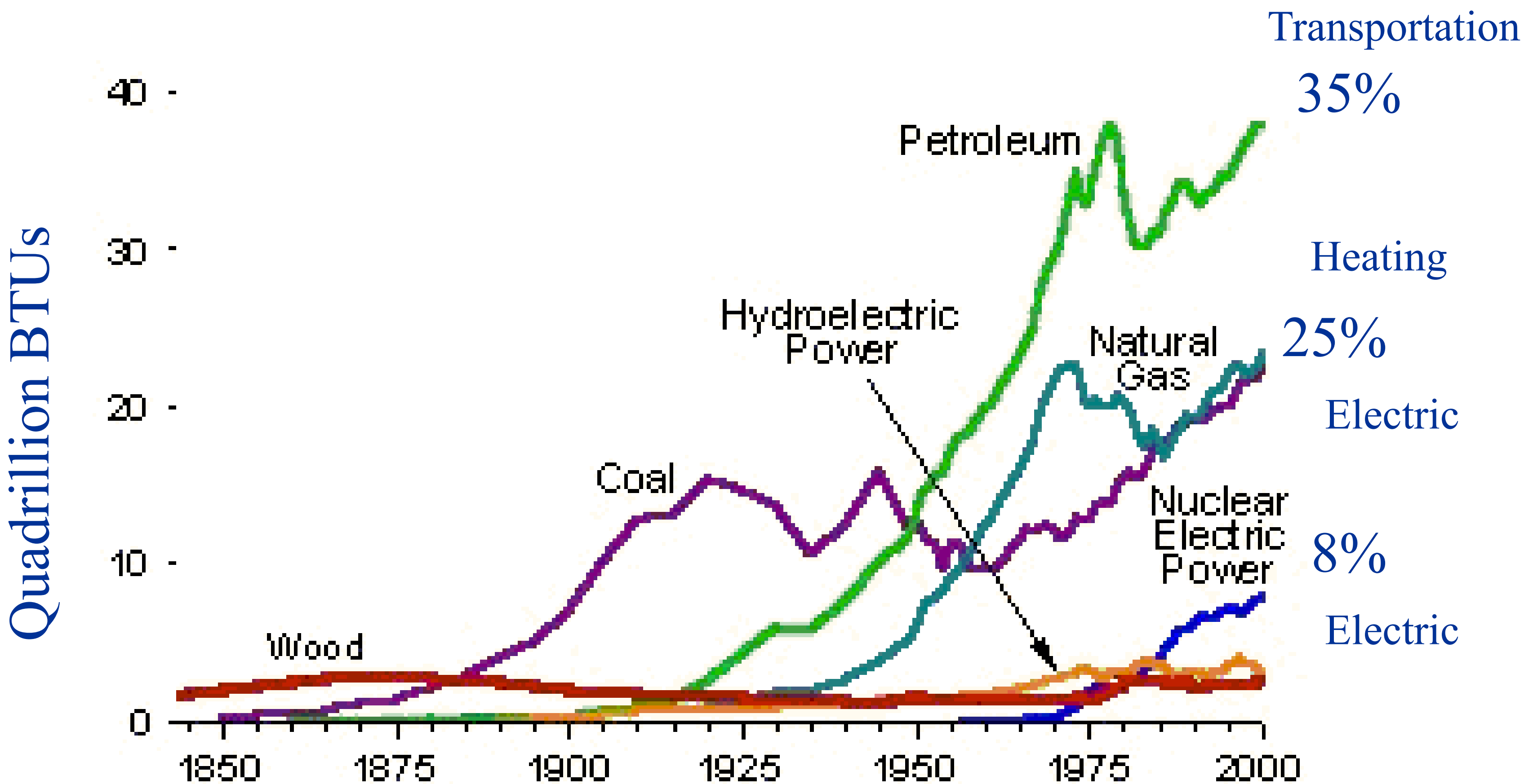
David Rutledge, an electrical-engineering professor at the California Institute of Technology who has studied global coal production, figures the U.S.has about half as much recoverable reserves as the government says, which would work out to about **120 years' worth**.

Carbon-Dioxide Levels



- ppmv = parts per million by volume
- Carbon-dioxide levels recover slowly
- What are the impacts of CO2? Are the limits achievable?

US Energy Consumption



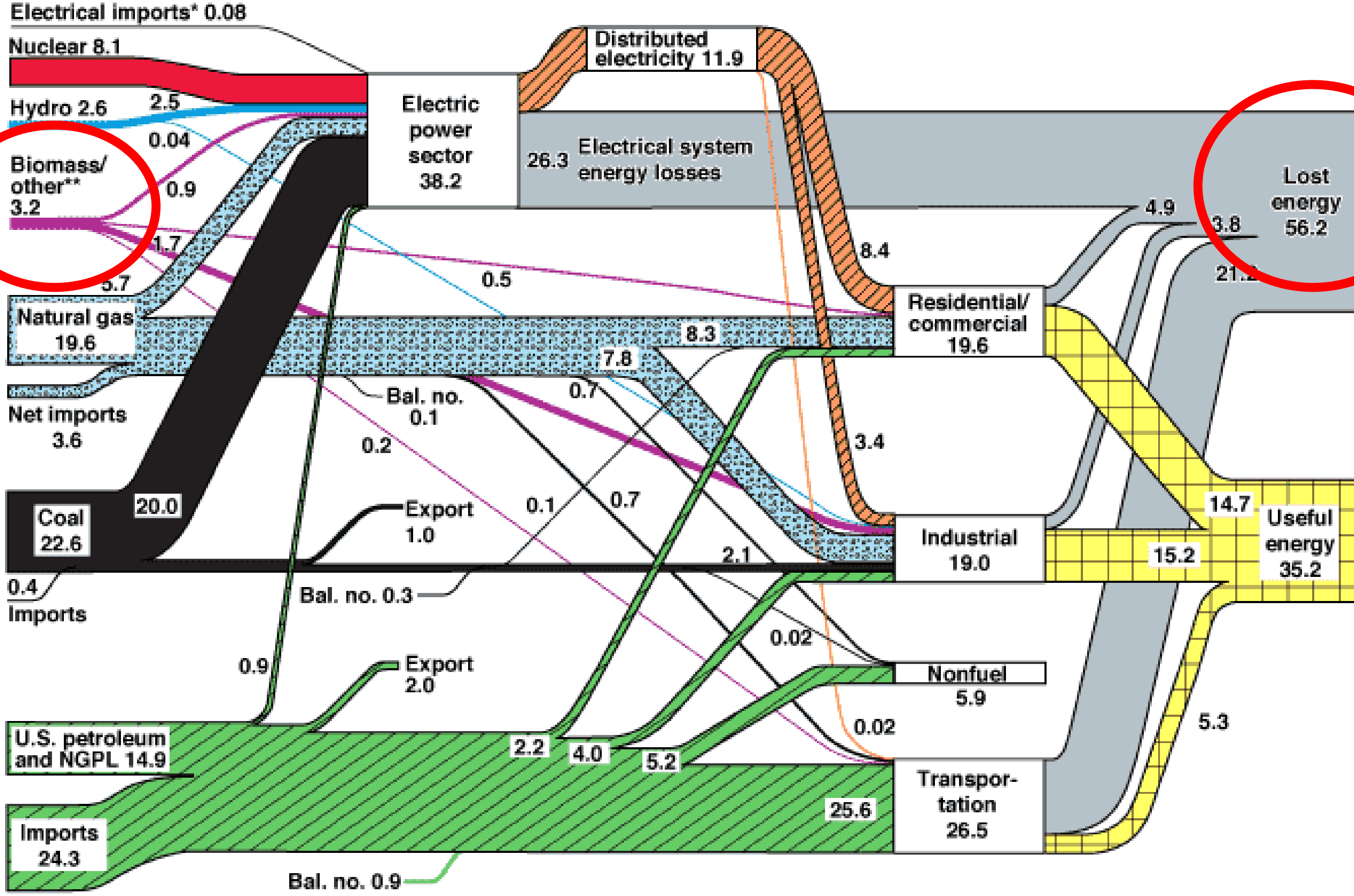
THE PROBLEM STATEMENT (?)

- Maintain 2-3%/yr GDP growth in this century
  - A combination of new carbon-emission-free primary power sources are needed
    - 100-300% over present fossil fuel sources by 2050
  - AND efficiency-improving technologies will be needed
  - Including <u>SMART Grid & Energy Storage</u>

- {to also keep global warming < 2 degrees Celsius* (CO_2 < 500 ppm)}
- {help maintain the food chain/life in the oceans}

What is the renewable status?

U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~97 Quads



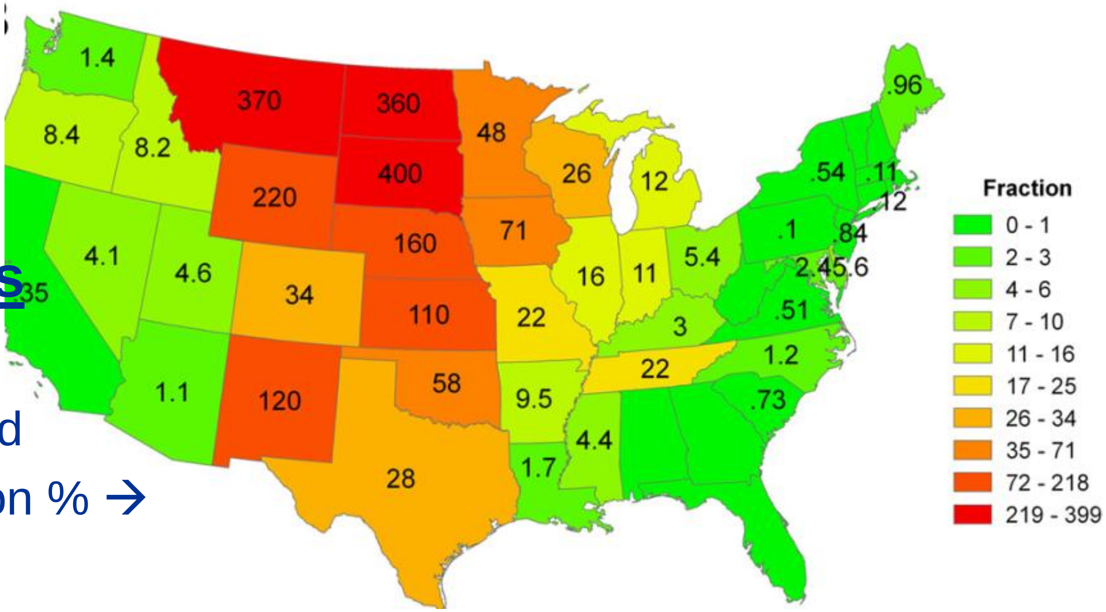
Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002.*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore
National Laboratory
http://eed.llnl.gov/flow

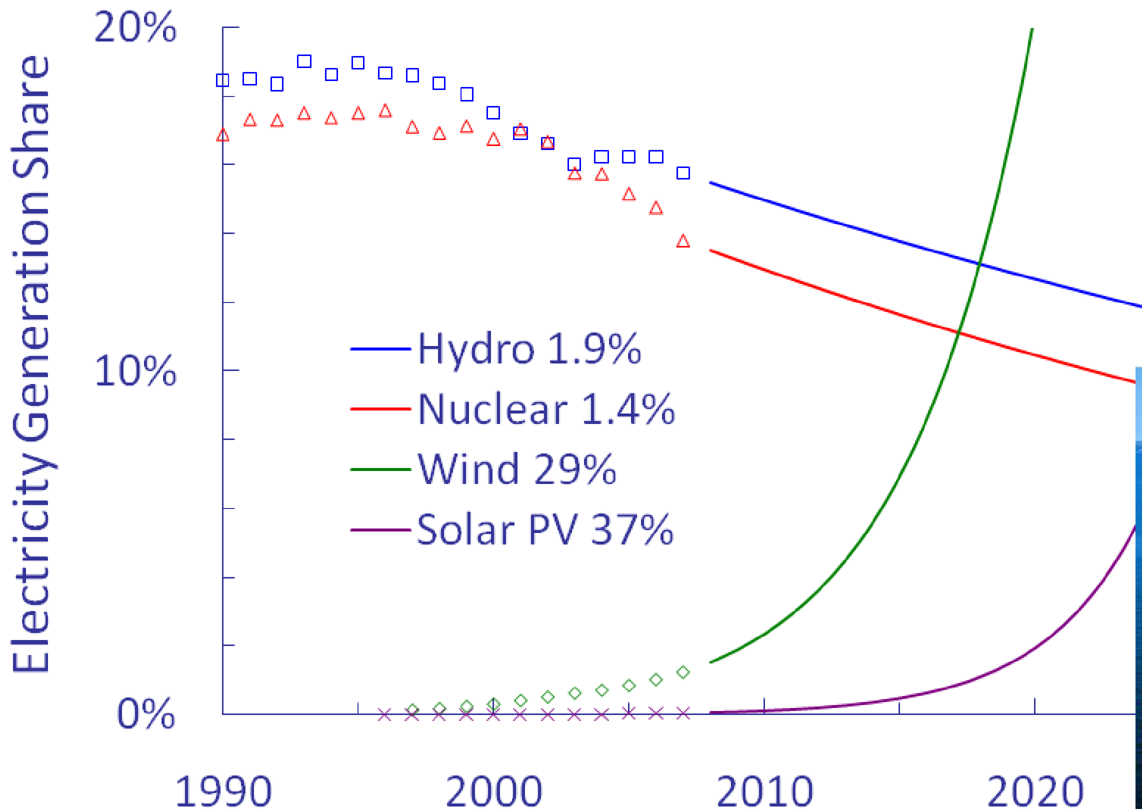
Wind: A Brighter Picture?

- **Global potential for wind-generated electricity**
- **Xi Lua, M.B. McElroya, and J. Kiviluomac, Harvard**
- **http://www.pnas.org/content/early/2009/06/19/0904101106**
- a network of land-based 2.5-megawatt turbines
- restricted to nonforested, ice-free, nonurban areas
- operating at as little as 20% of their rated capacity
- could supply >40 times current worldwide consumption of electricity
- **<u>>5 times total global use of energy in all forms</u>**

Excess LAND Wind Production % →



Trends for Alternatives

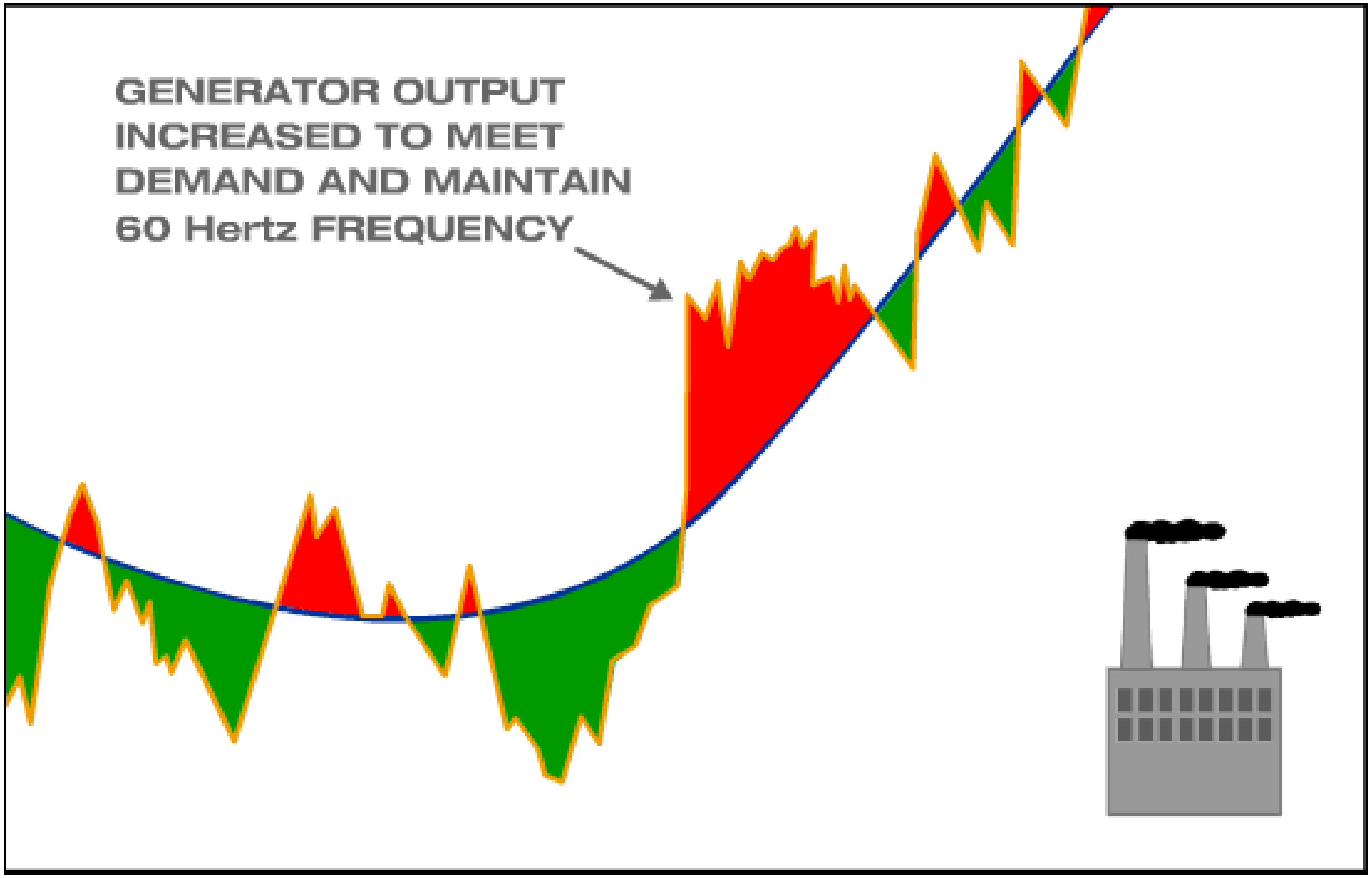


- These are the compound growth rates for the last ten years
- The comparable growth rate for world electricity has been 3.6%
- No production trends yet for fossil-fuel alternatives like oil shale and methane hydrates. Previous predictions of imminent substantial production have been wrong.

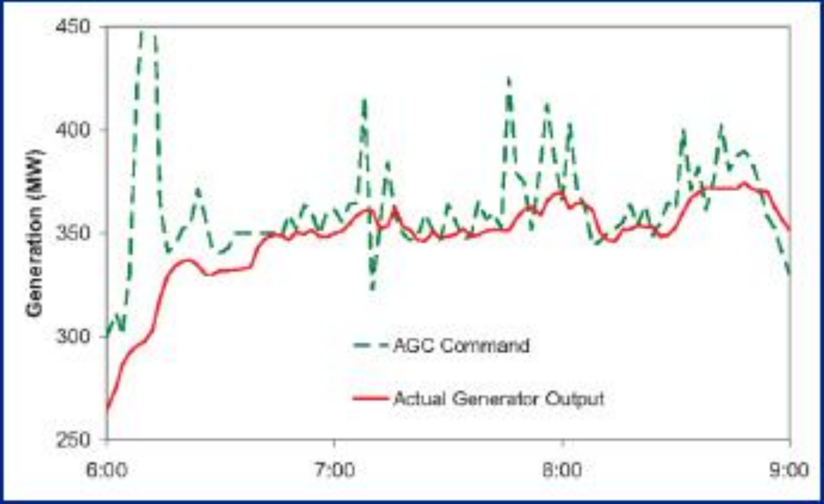
Are flywheels a key technology for renewable energy?

Beacon– Frequency Regulation

Flywheels and Frequency Regulation - (2:44)

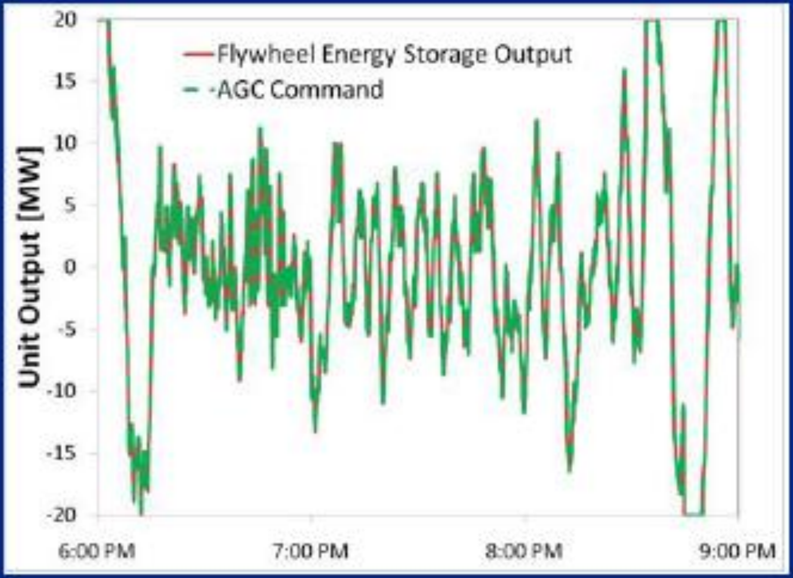


Fast Regulation: Speed Matters…



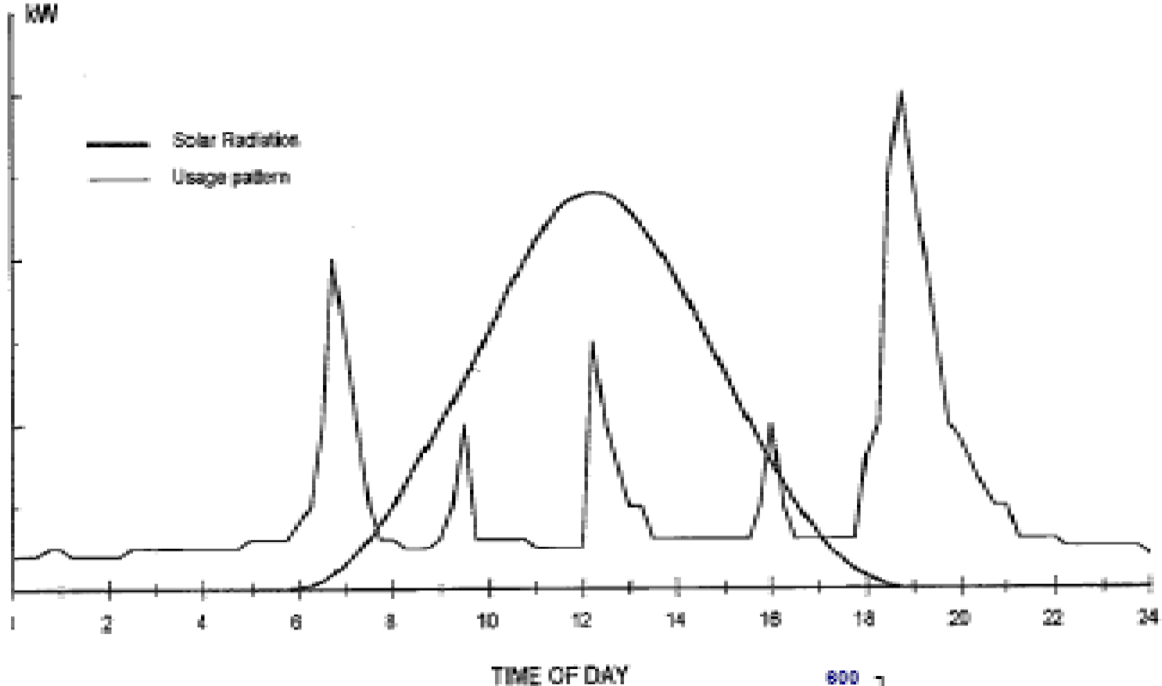
A coal fired power plant poorly following an AGC regulation command signal

Energy Storage accurately following an AGC regulation command signal



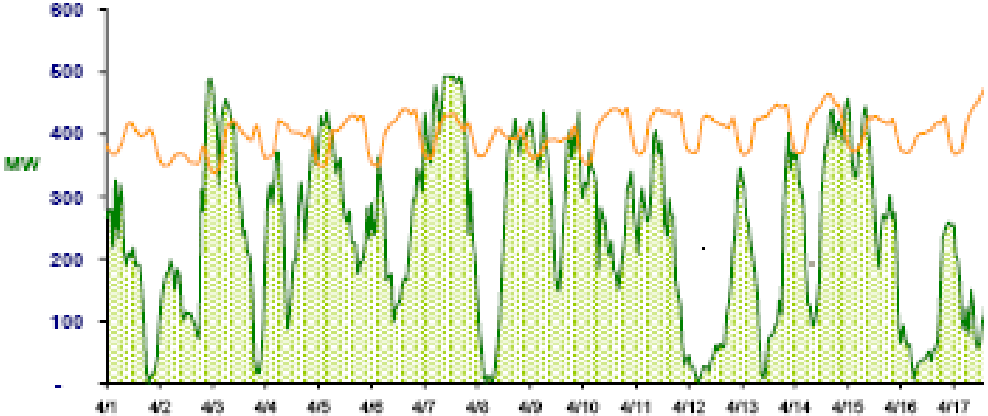
Flywheels provide near-instantaneous response

Electrical Usage Pattern vs Solar, Wind



Energy Storage is Needed to Match the Load to Demand

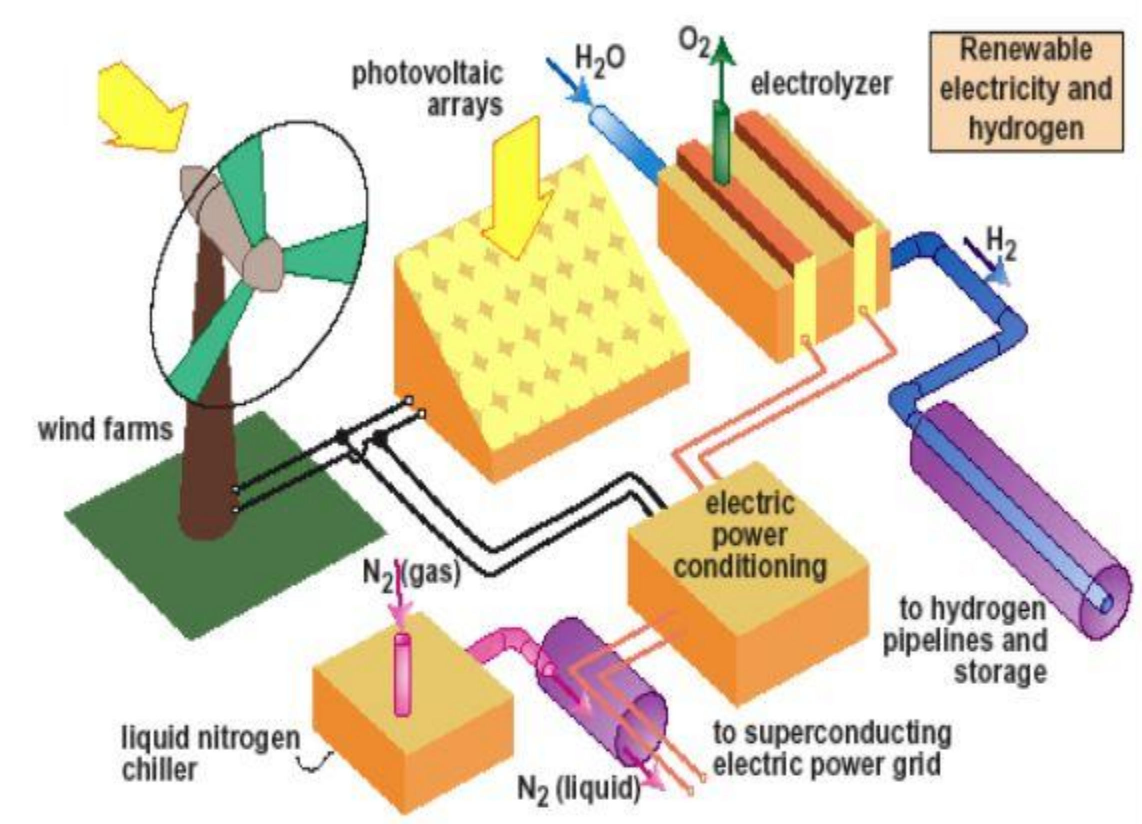
Hours



Days

Dr. Martin Hoffert

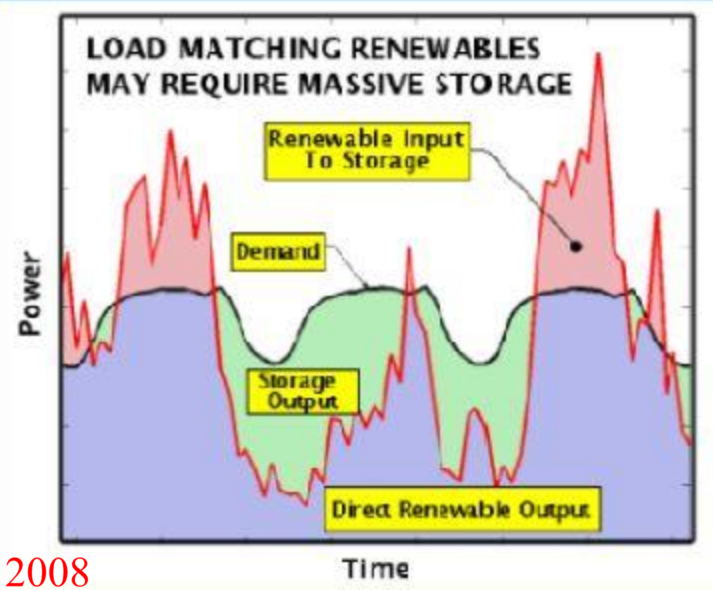
- Emeritus professor of physics at New York University
- “We are living in two parallel worlds:
  - a world of …what we should be doing about climate change and energy
  - and the real world of what we are doing.
- **In regard to renewables, we’re building the wrong infrastructure.**
- If we want renewable energy, then I think the greatest potential is from **solar and wind**, which are intermittent, dispersed and low power density sources, but we don’t have the right kind of electric utility grids to accommodate those energy sources.
- **we’re not talking about what types of grids will provide the transmission and storage capabilities to allow renewable energy to provide roughly thirty percent of our nation’s energy.”**



• Denmark, world leader in wind-generated electricity, achieved ~ 20% penetration largely by backing-up intermittent winds with pumped storage in Norway's 100% hydro-powered grid.

•BUT: Hydro is near-saturation worldwide & not an option in most locales

MASS-PRODUCED &WIDELY DISTRIBUTED SOLAR PV AND THERMAL ALONG WITH WIND COULD GENERATE 10-30 TW GLOBALLY EMISSION-FREE IF TRANSMISSION & STORAGE PROBLEMS ARE SOLVED

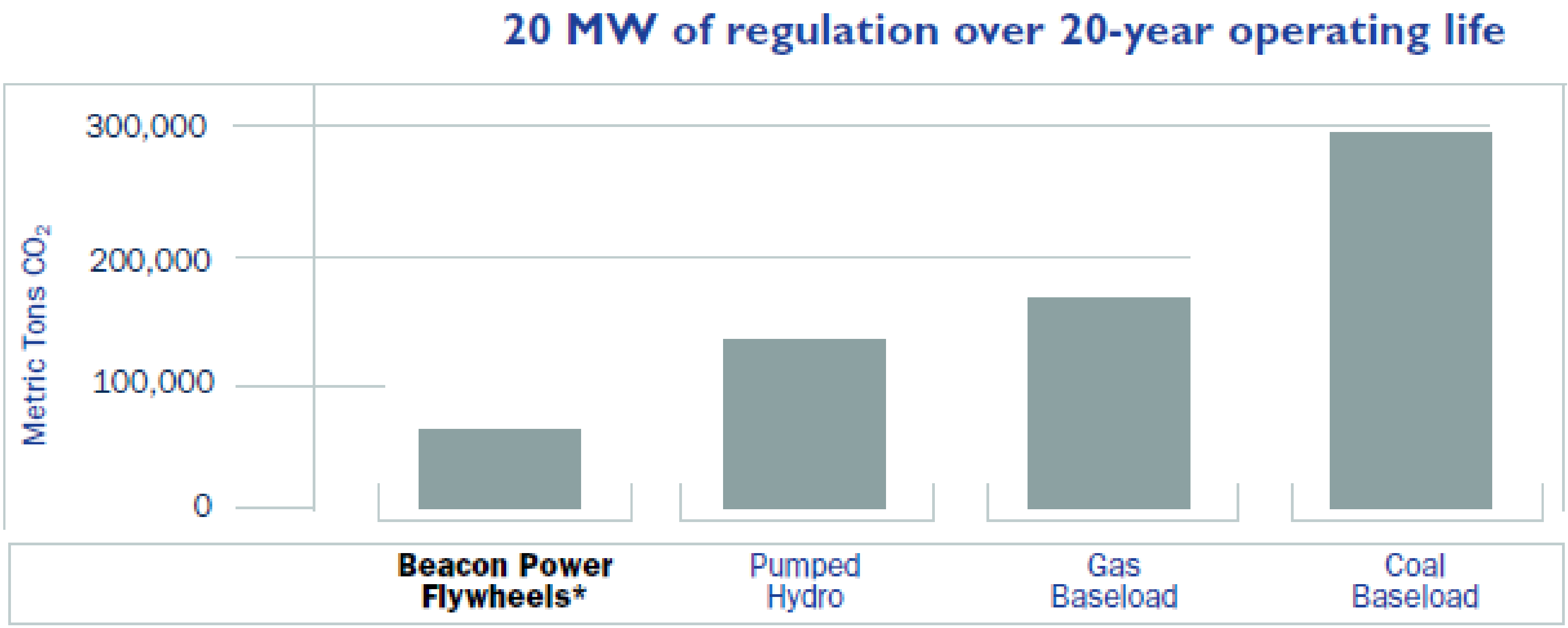


Marty Hoffert, NYU, "Energy from Space: The Case for R&D", Dec 2008

Ohio Hydroelectric Power Plant Scrapped

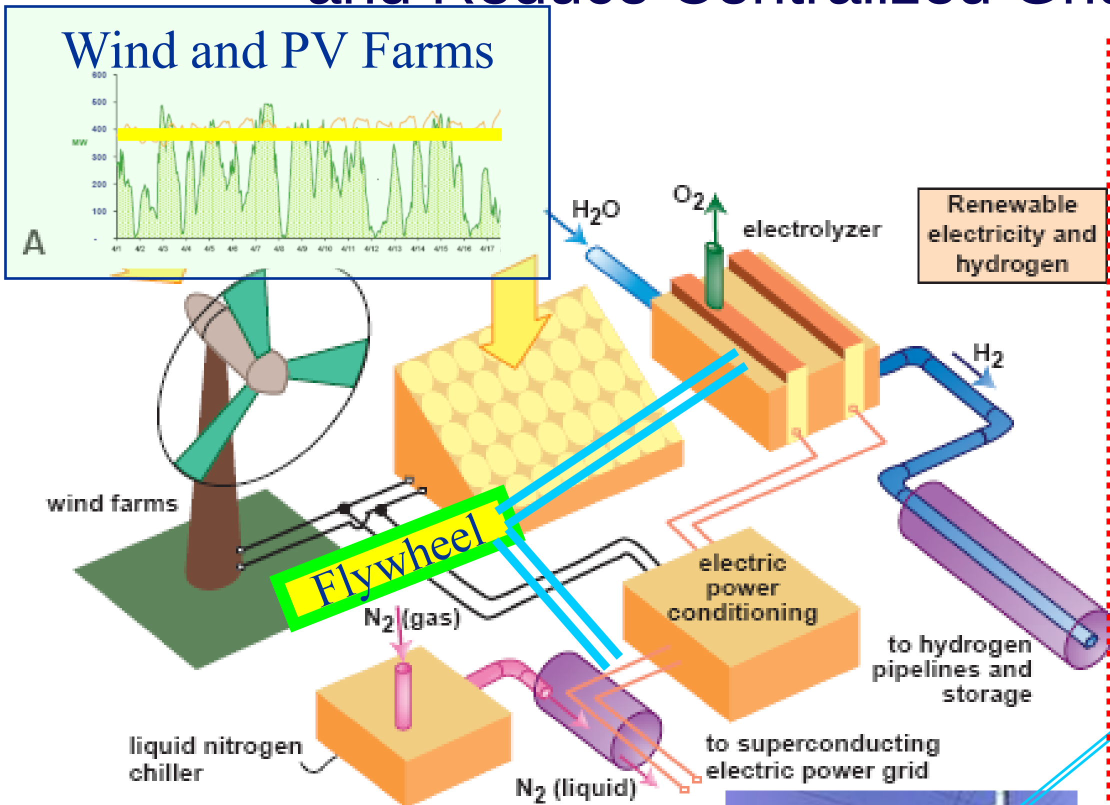
- **Hydroelectric power plant at Gorge Metro Dam is scrapped after EPA, Summit County Metro Parks, environmentalists complain**
- **by Michael Scott/Plain Dealer Reporter Wednesday June 24, 2009**

Beacon Power – Grid Regulation Technology
Comparison of C02 emissions



www.beaconpower.com

Flywheels Enable Decentralized Renewable Energy and Reduce Centralized Grid Costs



- Load Level
- Improve Battery Life/design
- Built In Power Conditioning

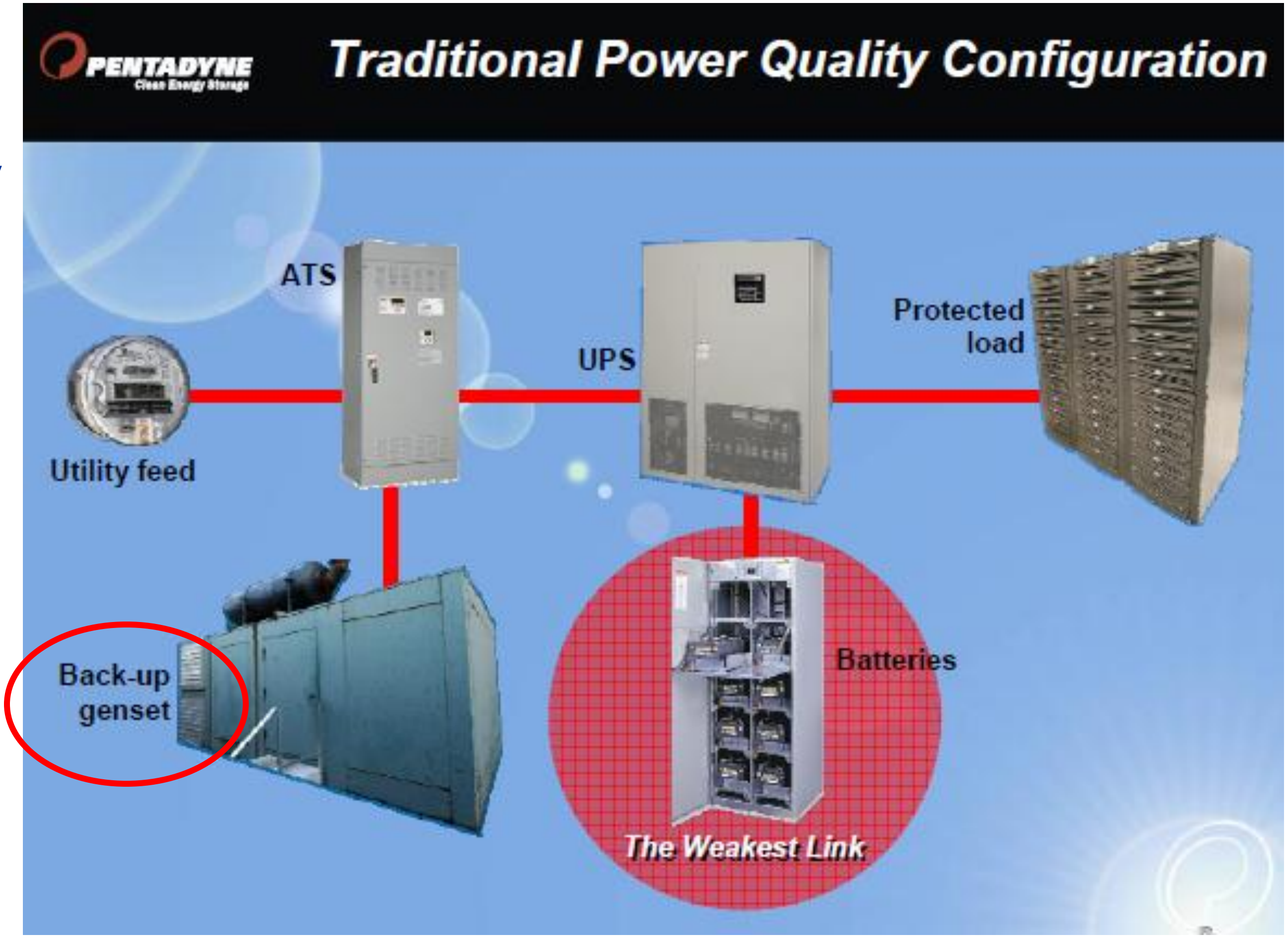
Martin Hoffert, et. al., “Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet

What are the Commercial Products?

Pentadyne #1 in Worldwide Sales of Flywheel Energy Storage Systems for UPS

Pentadyne Flywheel Energy Storage Fleet Exceeds 4M Operating Hours

Over 750 Units Sold



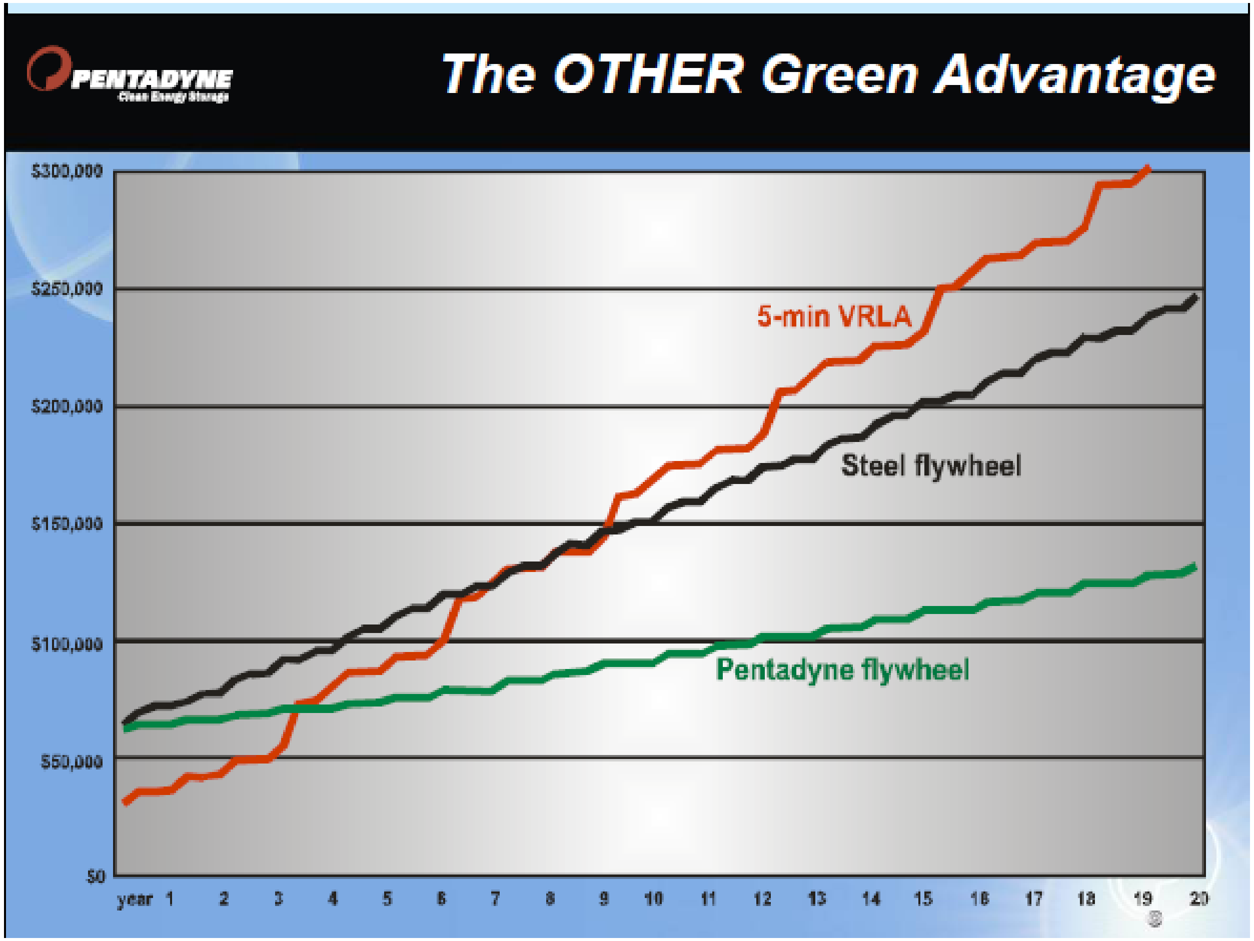
www.pentadyne.com

PENTADYNE
Clean Energy Storage

Pentadyne Overview

- Innovative clean energy storage for UPSs & energy recycling
  - Multiple innovation awards for both the product and company
- Proven product in volume production
  - >750 units sold and shipped
  - >400 in the last 18 months
  - #1 in flywheel production
  - #1 in staff/talent focused solely on flywheels
  - Nearly 4 million hours of proven reliable fleet operation

- Top channel partners
  - World's leading UPS manufacturers in the U.S., Europe and Asia



Each Pentadyne flywheel will save more than $100,000 in operating costs over that of our nearest competitor's product. Compared to lead-acid batteries, the savings per cabinet are more than $150,000. The above cost comparison is inclusive of operating energy costs, maintenance and HVAC energy use, but not inclusive of ancillary equipment costs, such as HVAC equipment, acid-spill containment, health & safety equipment, floorspace, fire hazard permitting, explosive gas sensors, etc.

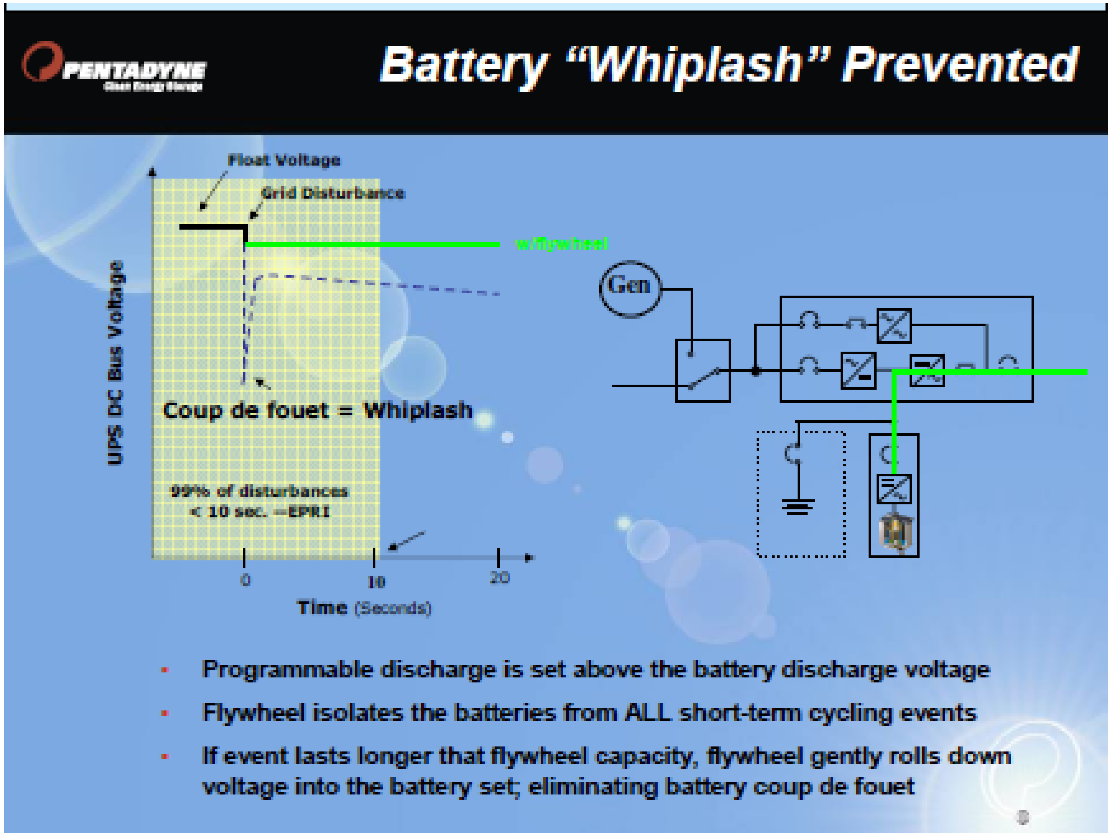
PENTADYNE
Clean Energy Storage

Critical Need: Storage vs. Generation

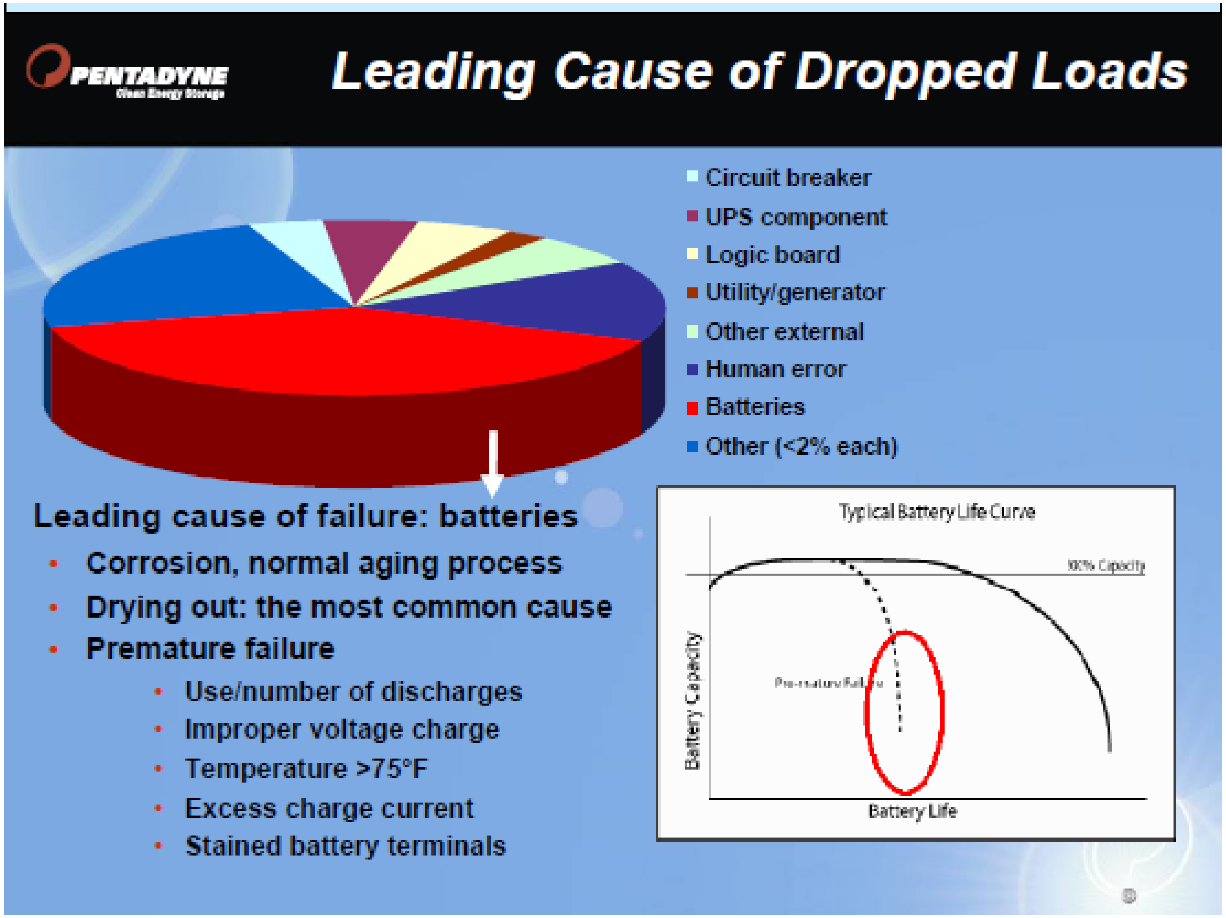
The 1st 10 seconds matter 100% of the time
The next 10+ seconds matter less than 1%

99%
of all power
disturbances
last less than
10 seconds

- EPRI confirms 99% of power disturbances are <10 sec.
- Energy storage matters 100% of the time; backup genset power is needed <1%
- IEEE data confirms outages >60 sec. occurred an average of only 1.5 times per utility customer over the last decade



When used in parallel with batteries, the programmable discharge voltage of the Pentadyne flywheel is set higher than that of the batteries. In an extended outage, the flywheel discharges to carry the load and smoothly transition it into the generator. The battery set sees a sub-second surface discharge 1/20th that of the flywheel current, but experiences no cycling. Running Pentadyne systems parallel with battery strings eliminates the coup de fouet effect that causes battery cells to age and fail. If an outage lasts longer that the flywheel runtime and a genset is not present, the flywheel will roll the voltage down into the lead acid batteries, avoiding that chemical whiplash event.



Problem is, batteries are the leading cause of dropped load incidents. As the weakest link in the chain, many facilities opt for a redundant string of batteries to hedge their bets. But the bottom line is that having two weak links in the UPS chain isn't much better than one.

PENTADYNE
Clean Energy Storage

A better way

		Pentadyne Flywheel	Lead-Acid Batteries
Lifecycle Cost	Installation cost	Low	High
	Footprint	Small	Medium to Large
	Maintenance	Very infrequent	Frequent
	Life expectancy	>20 Years	2 – 4 years
	Standby energy use	Low	Low
	Air conditioning cost	None	Medium
Reliability	Recharge	Very rapid	Very slow
	Diagnostics and monitoring	Precise, real-time	Speculative
	Known state of charge	Yes	Unpredictable
	Dropped load MTBF	>900,000 hours	~10,000 hours
Environment and Safety	Operating temperature range	Broad	Narrow
	Hazardous materials	None	Yes
	Explosive and toxic gas emissions	None	Yes
	Disposal requirements	None	Yes
	Ventilation requirements	None	Yes

PENTADYNE
Clean Energy Storage

Green Technology

"Lead is ranked 2nd in US for all hazardous materials and requires proper disposal" - *EPA*

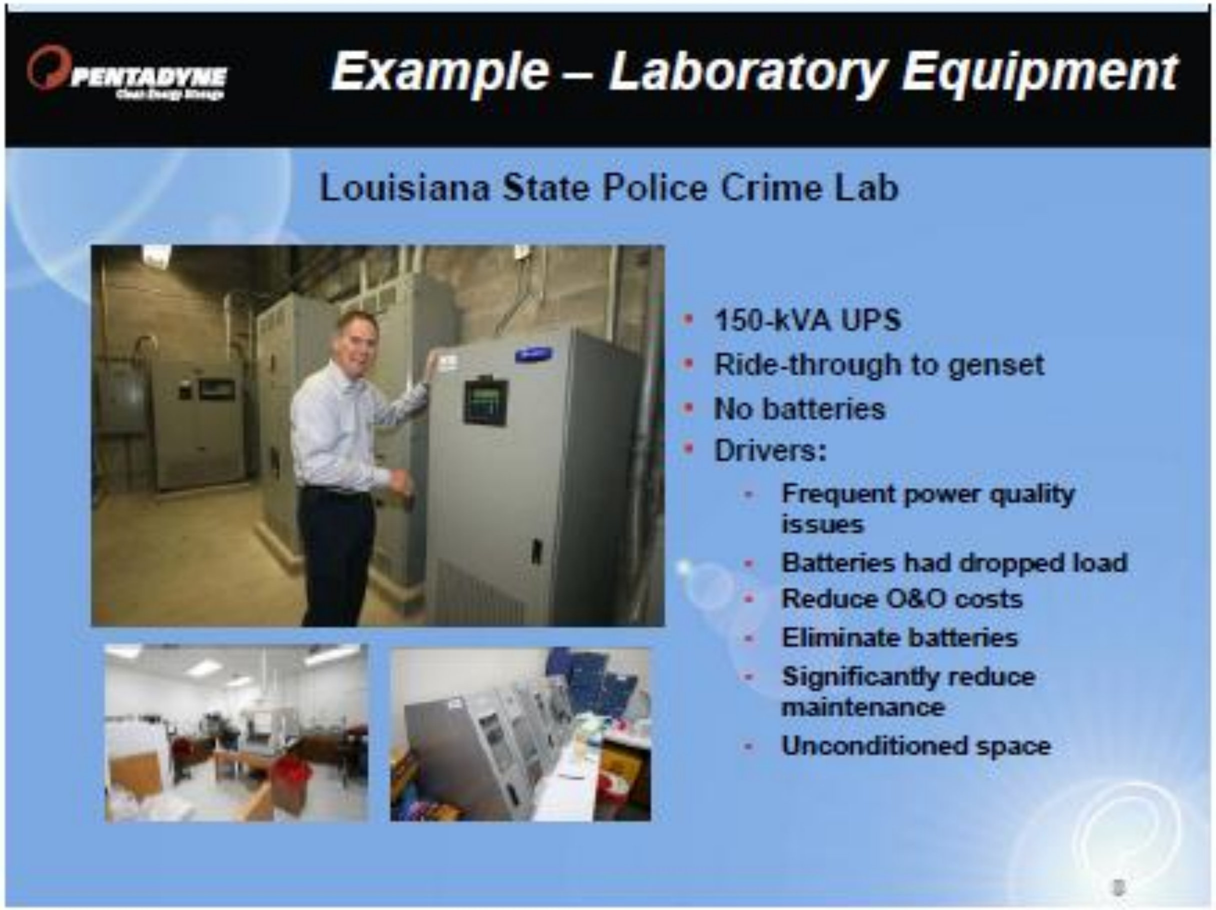
- **Elimination of Hazardous Materials**
  - No lead mining, smelting, transport, etc.
  - No lead disposal
  - No sulfuric acid disposal
  - No greenhouse gas emissions
  - No disposal/replacement after only a few years of service
    - Lasts 20+ years

08
GoingGreen
100
Winner

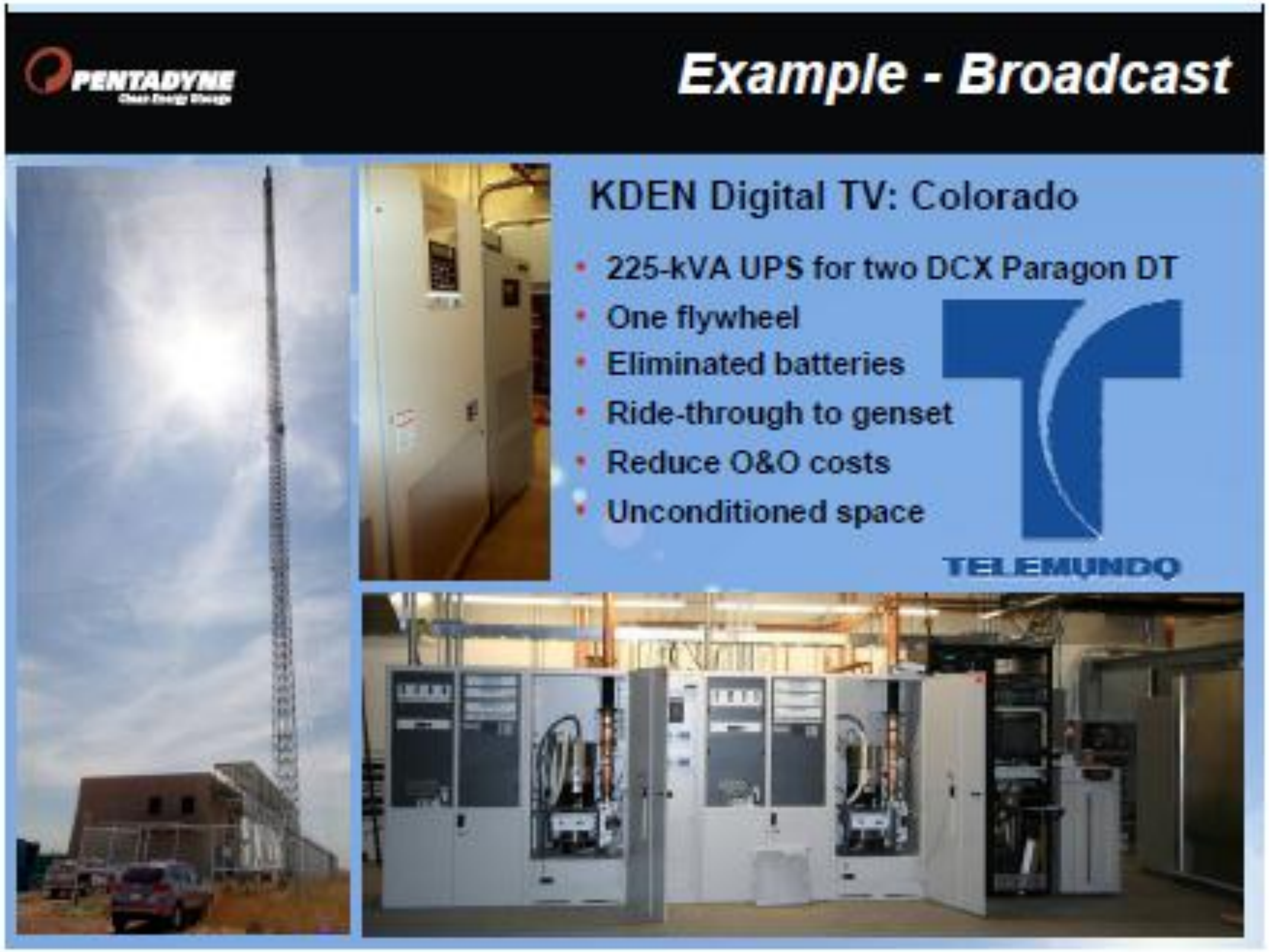
- **Energy Reduction**
  - Only 250 W "float" charge
    - 1/10th that of other flywheels
    - Annual savings
      - 20,000 kWh/unit deployed
      - 26,000 lbs of carbon emissions/unit deployed
  - Rapid recharge in seconds
  - No cooling requirements

Norman Y. Mineta San José International Airport serves the Silicon Valley and Greater San Francisco Bay Area. The airport moves about 10 million passengers per year. The Pentadyne system there operates in parallel with a redundant set of UPS batteries. In this configuration, the Pentadyne system is the first line of defense against all power issues, isolating the batteries from any such events.

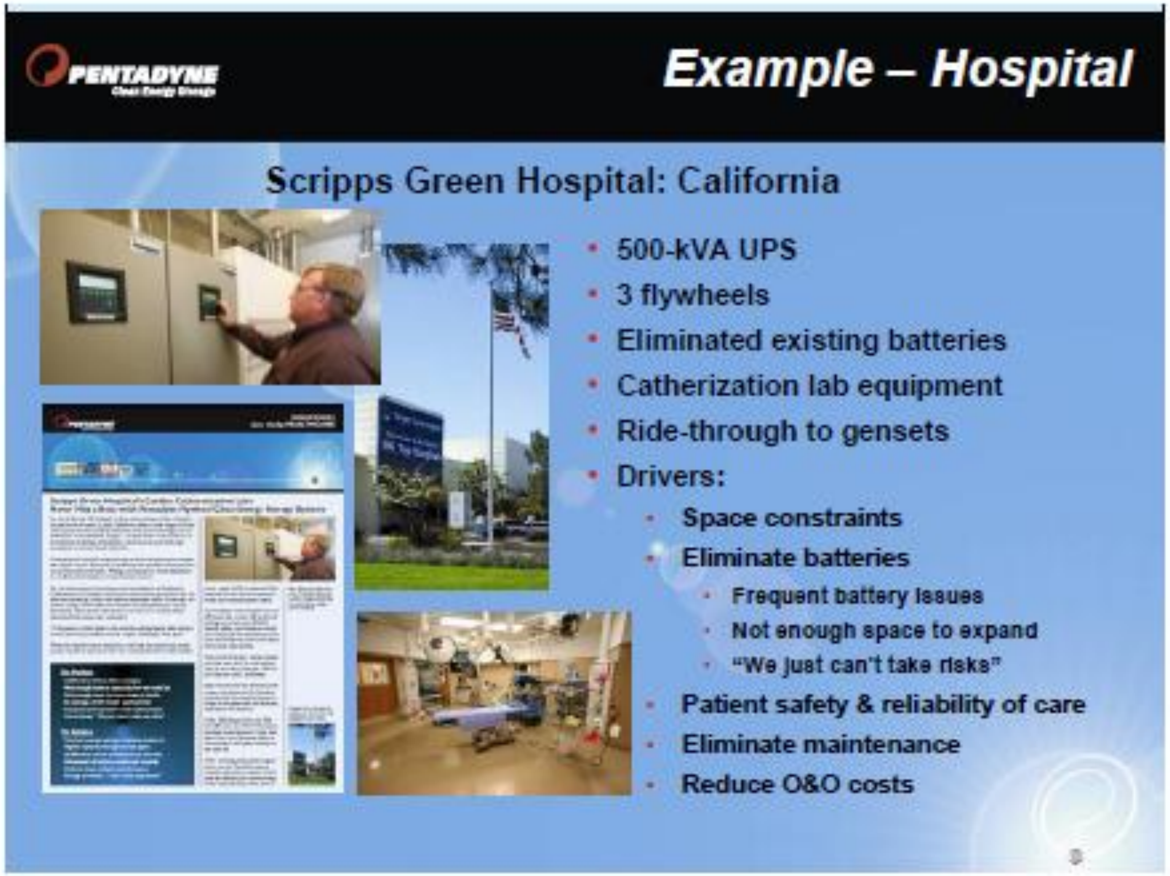
Cache Creek Casino outside of Sacramento is one of the largest Native American gaming facilities in the United States. Situated in a rural area, they were at the end of a PG&E utility line and often suffering very poor power quality and reliability. Frequent power interruptions were killing their battery sets at an alarming rate. They now use a bank of five Pentadyne-made Liebert FS systems on their 1 MVA Liebert 610. Because the FS array can smoothly roll off voltage into a battery set if the generators could not come online, this enables the use of a ***3-minute*** battery set – something you could never do with batteries alone due to coup de fouet issues.



This high-tech crime investigation lab in Baton Rouge has a range of laboratory devices on their UPS. The UPS, switchgear and energy storage are all in an unconditioned power room off the main building. Considering the heat they get down in Southern Louisiana, that's no place for batteries. But the flywheel has an ambient operating temperature range even greater than that of the other equipment. And because it is so energy efficient, it contributes very, very little to the heat in that room: only 1,000 Btu/hr.



This NBC-Telemundo digital TV transmission site in a remote area outside of Denver has eliminated the many frequent trips previously needed to diagnose battery cell issues and wire in replacement batteries.



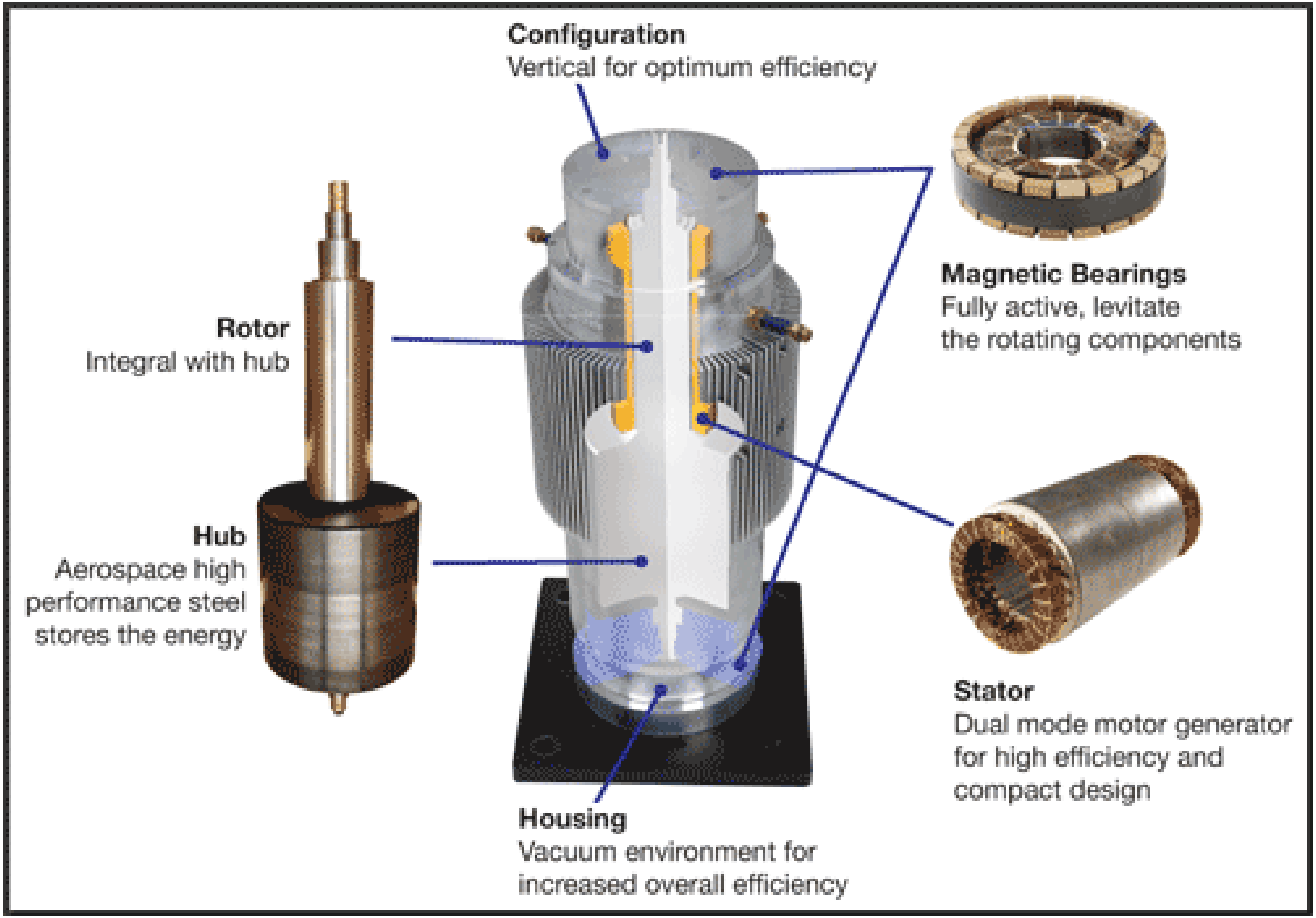
Heart catheterization lab equipment is notorious for pulse loads that UPS systems just can't rectify quickly enough, so energy for those sub-second inrushes have to come out of the UPS energy storage. With hundreds of those occurring every week, it's no wonder that cath labs, MRIs, CT scanners and other imaging equipment burn through so-called 10-year VRLA batteries in just 12-18 months. Flywheels, on the other hand, are completely unaffected by such frequent cycling.

Energy Recycling - VYCON

- In ship & rail yards, cranes move containers every min
- Usually powered with on-board diesel generator set
- Regenerate power during braking and lowering rather than resistor bank
- Cranes, Rail, Wind, Elevators, …..

www.vyconenergy.com

Vycon


Configuration
Vertical for optimum efficiency
Magnetic Bearings
Fully active, levitate
the rotating components
Rotor
Integral with hub
Hub
Aerospace high
performance steel
stores the energy
Stator
Dual mode motor generator
for high efficiency and
compact design
Housing
Vacuum environment for
increased overall efficiency

Our Primary Business Model

Beacon POWER

- Selling services that are essential to the grid (24/7)
- Serving large open and established markets
- Endorsed by the customer (i.e. grid operators)
- Achieves carbon reduction
- NOT dependent on selling equipment
- NOT dependent on an "emerging" market
- NOT dependent on subsidies

Government Policy Support

Beacon POWER

- Department of Energy stimulus funding
  - More available than in previous 20 years
- Storage Technology of Renewable and Green Energy Act of 2009 (STORAGE)
  - Proposed by Sen. Ron Wyden (D-Ore.) as S.1091
  - 20% credit for energy storage – <u>including flywheels</u>
- Proposed Renewable Electricity Standard (RES)
  - Waxman – Markey bill H.R. 2454; first national standard for renewable energy and energy efficiency
- Grid Access Act of 2009 (net metering)
  - Proposed by Sen. Menendez (D.-NJ) as S.989

DOE Stimulus Funding

- Stimulus grants for Smart Grid project(s)
  - Have submitted proposals for ARPA-E grants
  - Will apply for energy storage for frequency regulation demonstration project ($40-50 million, DOE FOA-36)
  - Will pursue other Funding Opportunity Announcements as they are released
- State-disbursed funds (from Stimulus or other)

ISO New England Status – 1st MW

Beacon POWER

- Alternative Technologies Regulation Pilot Program
  - Began commercial operation at start of program in Nov. 2008
  - First regulation services revenue being generated
  - ISO NE now using modified and improved control signal
  - Negotiated much lower cost for electricity consumed

ISO New England Status – 2nd MW

Beacon POWER

- Second MW (10 flywheels) now running outside
- Expect to be online later this month
- Will run and earn revenue until deployed to NY or OH

20 MW New York ISO Status

Beacon POWER

- New NYISO market rules completed and implemented for energy storage to provide regulation service
- 20 MW plant interconnection application in process
  - System impact study is complete
- $2 million awarded by NYSERDA for 1st MW in Stephentown
- 1 MW permits and approvals in place (NYSEG)

PJM Project: 1 MW with AEP

- 1 MW system on a 13.2 kV distribution circuit
- Located at AEP's R&D site in Groveport, OH
- Interconnection process complete
- Planned for construction start in late 2009
- PJM is upgrading control signaling for energy storage

Beacon will analyze future shipboard energy storage needs for NAVY-- a mini-grid

http://earth2tech.com/2009/02/04/flywheel-energy-storage-hits-the-high-seas/

R&D Projects Update

Beacon POWER

- Tehachapi Wind Power Integration Project
  - Evaluate how energy storage can help relieve constrained transmission capacity in wind farm
  - Prime contractor requested 12-mo. extension
  - Beacon ready to deliver flywheel system when needed; expected shipment 2H 2009
- PNNL Phase II contract
  - Co-optimize flywheel energy storage and hydropower
  - Mitigate wind and solar power intermittency for Bonneville Power Authority and California ISO

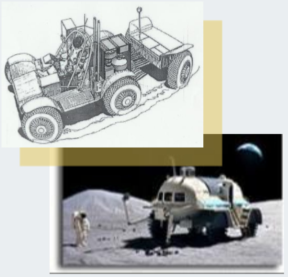
What are the NASA flywheel program and applications?

Flywheels, Solving a Tough Problem

- Future NASA missions require a new generation of reliable, long life and low maintenance systems designed to function as low as -147 ºC
- No energy storage exists that can provide practical discharge rates within a wide temperature range without significant auxiliary equipment

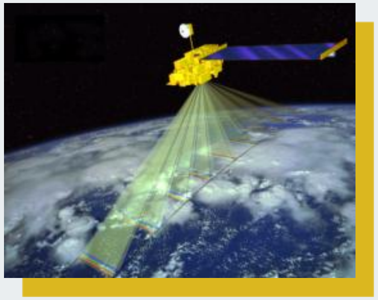
Flywheel Advantages

- High specific energy
- 15 year life
- High peak power with no life impacts (for excavation, steep climbs, reboost)
- Large (-45 to 50°C) temperature range
- Fault Isolation eliminates electronics
- Fault tolerance at component level
- Built in health monitoring
- Known state of charge

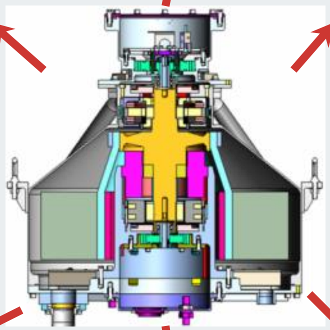


Rover Energy Storage with Large Peak Power for ISRU Excavation

High Peak/Pulse Power for Advanced Propulsion Systems



Integrated Power and Attitude Control for Low Earth to Lunar Orbit Satellites



ISS

Tethers for Satellite Reboost and Orbit Transfer

Lunar Energy Storage

Flywheel replacement for ISS batteries would save over 250 million in hardware, launch costs

Space Flywheel Applications

- ISS Energy Storage & ISS Electric Propulsion, Stage Transfer
  - Significant ISS energy storage life cycle cost reductions
  - Uses solar energy rather than launch propellant to enable propellant-less reboost and cheap, efficient, two-way transport
- Satellites with Combined Attitude Control/Energy Storage
  - High specific energy, 15 year life, eliminates attitude control system
- Lunar Energy Storage
  - 25 kWe for 14 days, 10X Peak Power capability, Fault Isolation to minimize electronics, extreme reliability, modular, launched for $3B , no disposal issues
- Lunar Mid to Large Size Rover Energy Storage and Excavation
  - 15 year life, Peak Power for ISRU excavation, wide temperature range
- Lunar and Mars Uninterruptible Power Supply
  - backup power for lunar missions and a Mars nuclear system to increase mission reliability until a methane/oxygen generator can be started

Battery Design Impacts for Comparative Analysis to 12.5kW LEO Flywheel System

100% DOD

Li Cell
120 Whr/kg

+

0% to 90% SOC
10year life

Battery Stack
108 Whr/kg

+

65% to 90% SOC
10 year life

Battery Stack
27.0 Whr/kg

Cell Impacts

Chg/Dischg Electronics, Cell Interconnects, Diodes etc.

Battery System
11.2 Whr/kg

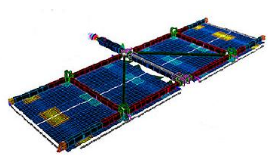
+

Battery and Electronic Input/Output Efficiency

Battery System
9.1 Whr/kg

Battery Impacts

Array Mass Oversize due to Taper Chg



System S.E.
8.0 Whr/kg

+

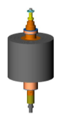
CMG Mass for Comparison to IPAC's

System S.E.
7.0 Whr/kg

System Impacts

Flywheel Design Impacts for Comparative Analysis to 12.5kW LEO Battery System

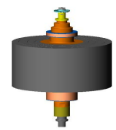
100% DOD



Rotor
117 Whr/kg

+

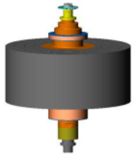
0% to 70% SOC 15year life



Rotor
81.8 Whr/kg

+

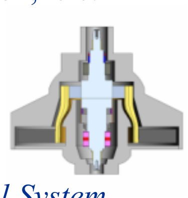
10% to 70% SOC
15 year life



Rotor
72.8 Whr/kg

Rotor Impacts

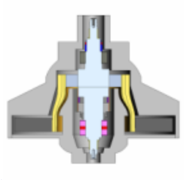
Power Electronics, M/G , M/B Suspension, etc.



Flywheel System
36.4 Whr/kg

+

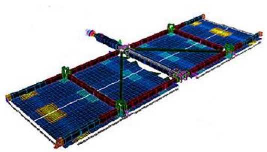
Flywheel and Electronic Input/Output Efficiency



Flywheel System
31 Whr/kg

Flywheel Module Impacts

No Array Mass Oversize



System S.E.
31 Whr/kg

+

No CMG Mass
IPAC's

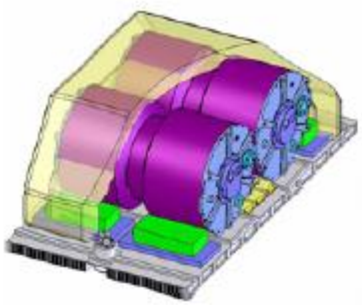
System S.E.
31 Whr/kg

System Impacts

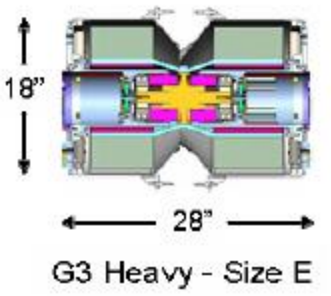
ISS Battery Trade Study

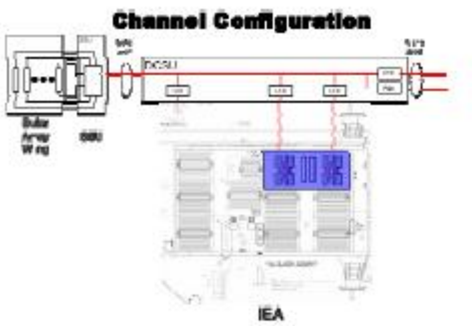
2 Flywheels would replace existing 6 NiH or 3 Li batteries

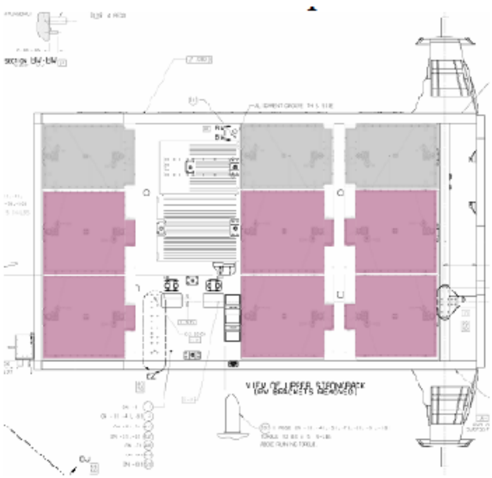
Flywheel ORU



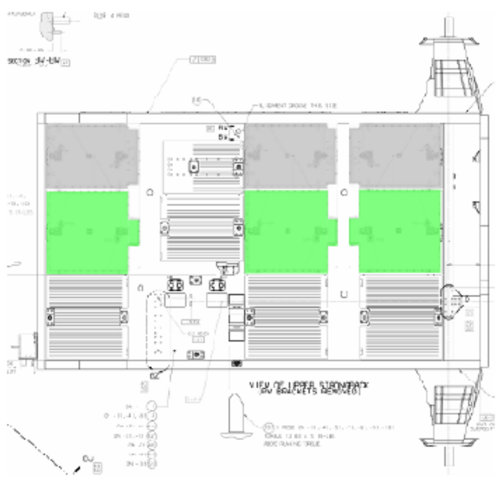
Flywheel Module



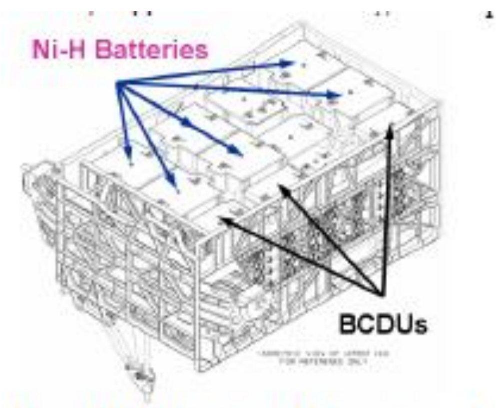




Baseline Ni-H



Lithium Ion



ISS Upmass Benefits

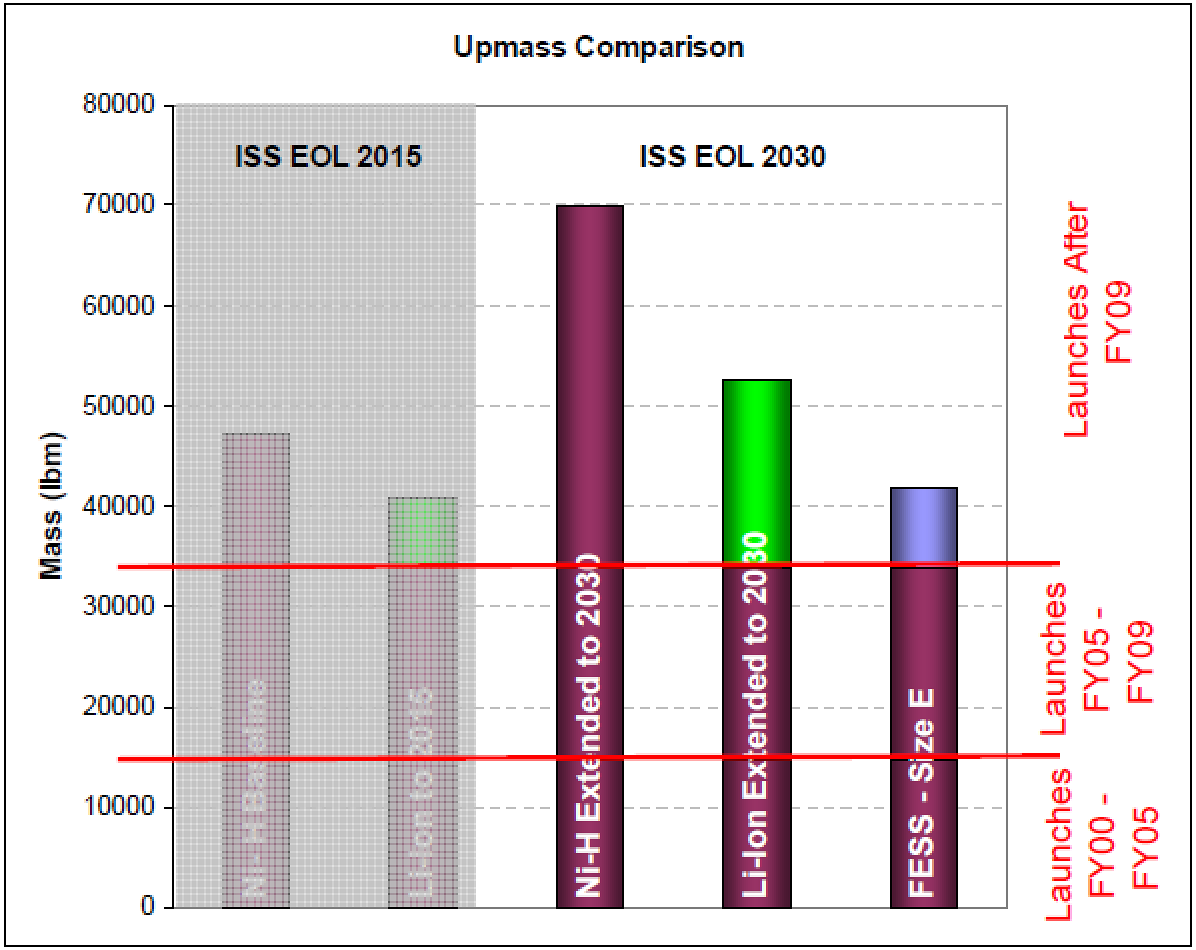


Figure 7 Upmass Benefits to ISS

Tether Reboost and Orbit Transfer

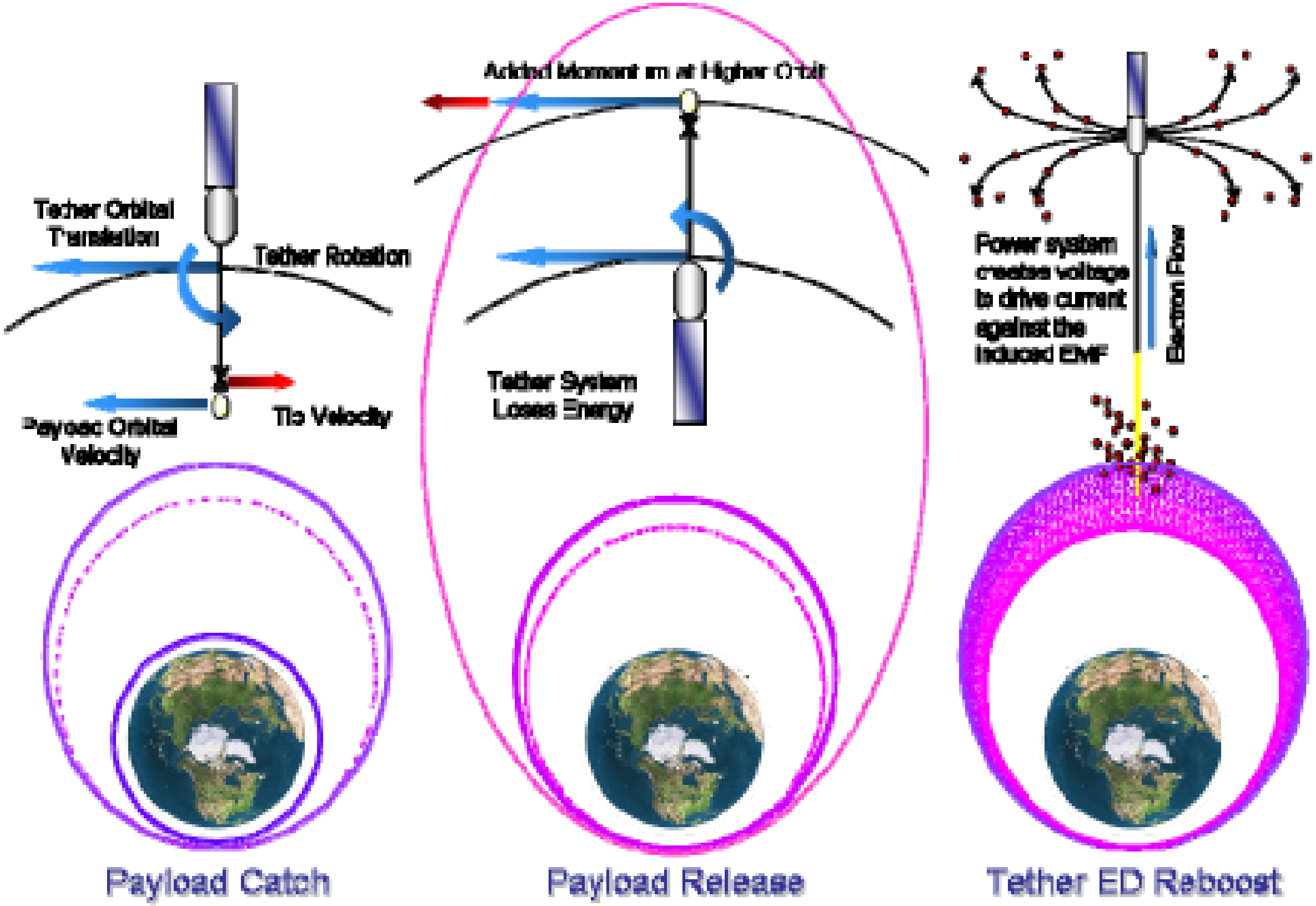


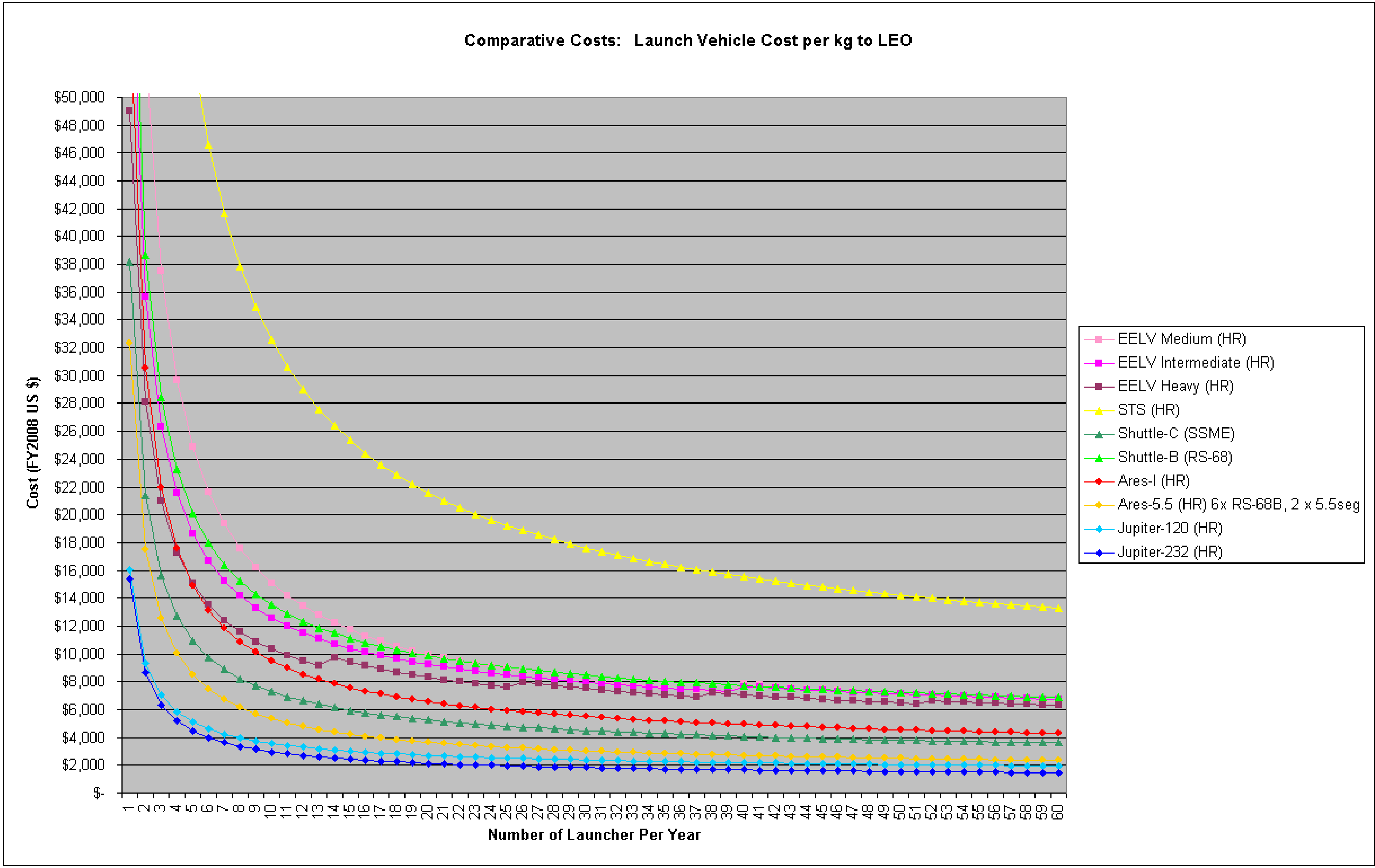
Figure 17 MXER Tether Basic Operation Modes

http://www.tethers.com/MXTethers2.html

Flywheels-Enabling Technology for Tethers

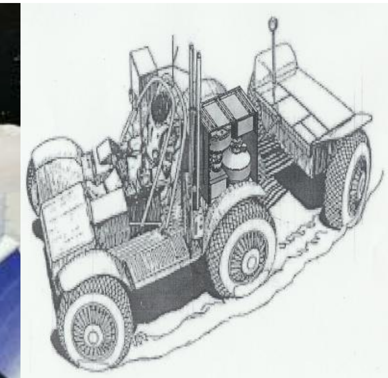
Nominal MXER Mission: Batteries vs. Flywheels			
1	Energy Storage Type	Battery (Li Ion)	Flywheels
2	Number of control nodes	1	1
3	Solar array power (kW)	49.0	46.1
4	Solar array area (m^2)	148	140
5	Solar array mass (kg)	605	569
6	Max power required (kW)	427	414
7	Total energy storage required (kWH)	134	126
8	Total energy storage mass (kg)	45400	2500
9	Total power electronic mass (kg)	427	414
10	Heat load excluding solar arrays (kW)	10	7
11	Radiator area (m^2)	29	21
12	Radiator mass (kg)	353	253
13	Total power system mass (kg)	46800	3700

Lunar Energy Storage


Comparative Costs: Launch Vehicle Cost per kg to LEO
Cost (FY2008 US $)
$50,000
$48,000
$46,000
$44,000
$42,000
$40,000
$38,000
$36,000
$34,000
$32,000
$30,000
$28,000
$26,000
$24,000
$22,000
$20,000
$18,000
$16,000
$14,000
$12,000
$10,000
$8,000
$6,000
$4,000
$2,000
$-
Number of Launcher Per Year
EELV Medium (HR)
EELV Intermediate (HR)
EELV Heavy (HR)
STS (HR)
Shuttle-C (SSME)
Shuttle-B (RS-68)
Ares-I (HR)
Ares-5.5 (HR) 6x RS-68B, 2 x 5.5seg
Jupiter-120 (HR)
Jupiter-232 (HR)

Flywheel Energy Storage Costs

Days	14 days
Power	25 kw
Energy	8400 kw-hr
Unit Energy	2.1 kw-hr
# Units	4000
Cost/Unit	50000
Recurring $	200 $M

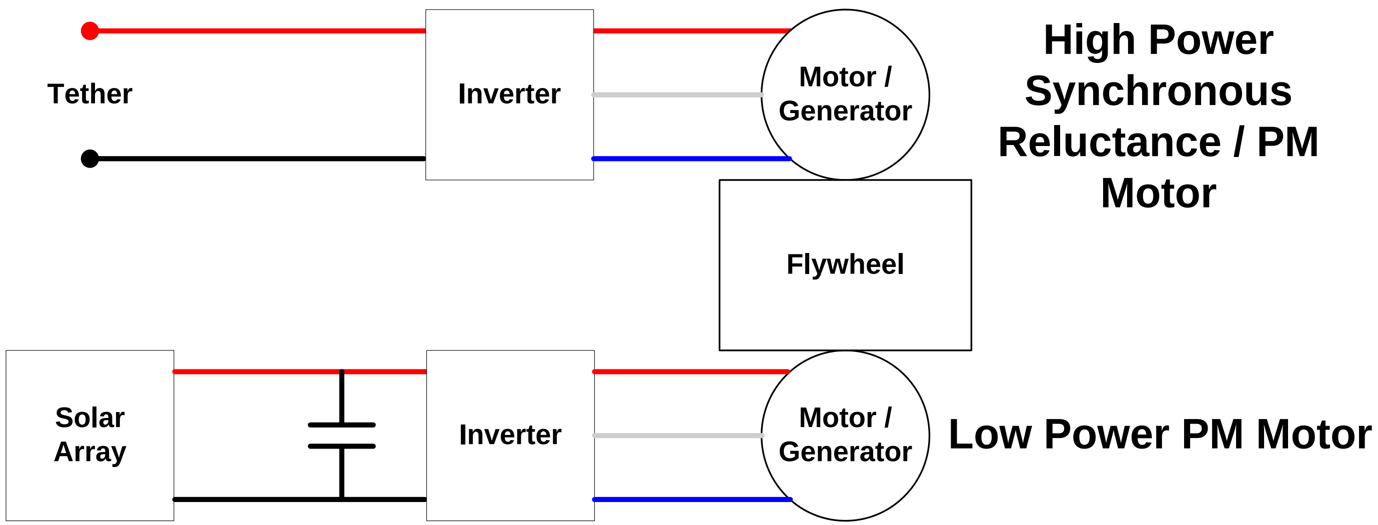


Flywheel Energy Storage Selection Depends on the Launch Costs and the Energy Density

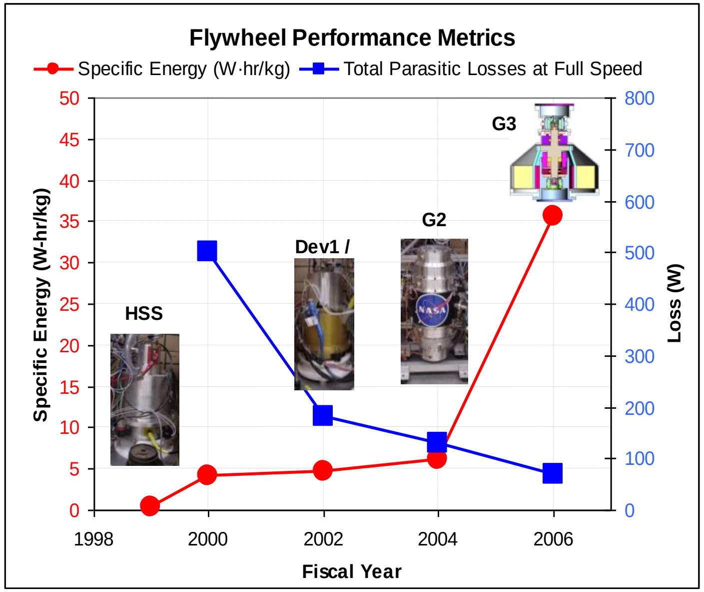
			Direct	Shuttle-C	STS
	Launch Cost		4000 $/kg	10000 $/kg	30000 $/kg
*70 LEO/ 20 Lunar	kg	mt	Launch Total ($M)	Launch Total ($M)	Launch Total ($M)
38 whr/kg	221053	221	3095	7737	23211
76 whr/kg	110526	111	1547	3868	11605
200 whr/kg	42000	42	588	1470	4410

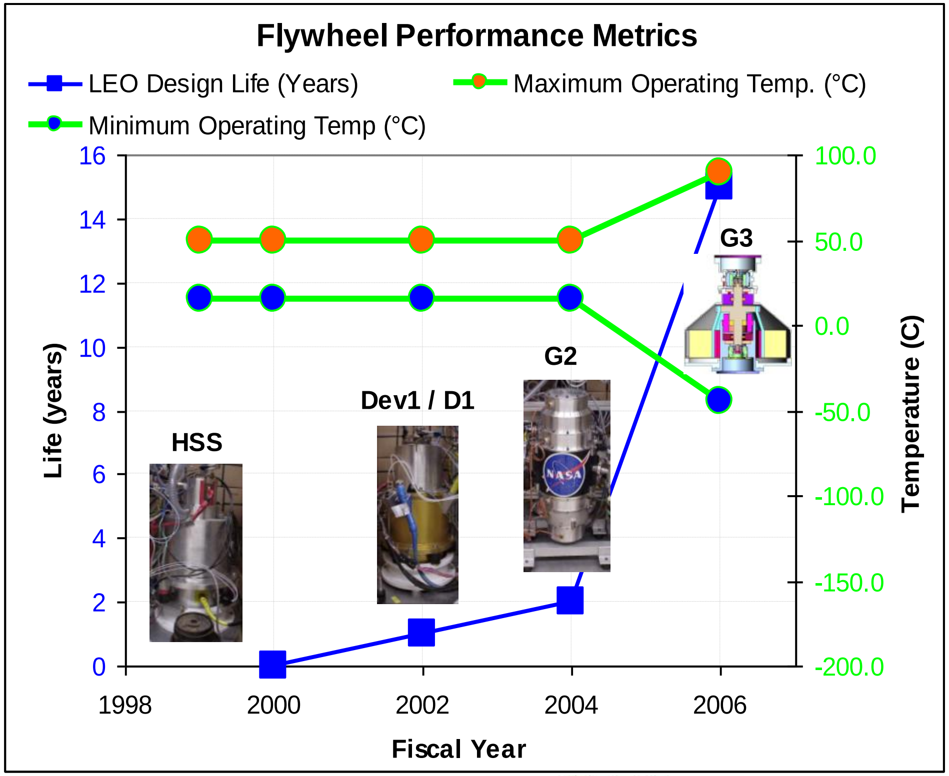
MXER Tether Flywheel Dual M/G Topology – Lunar Grid?

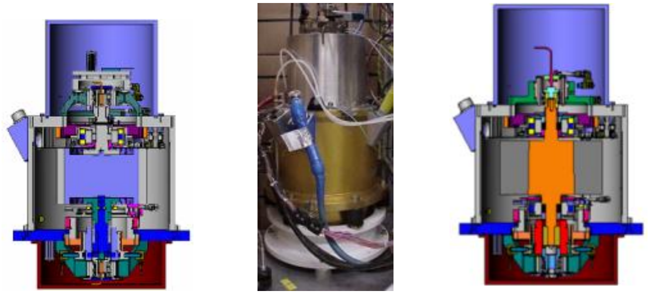
- Two Possible Topologies: all Permanent Magnet and a PM/reluctance option
- All-PM would be a single M/G with separate windings for the low and high voltage subsystems



Glenn's 8 yr Heritage

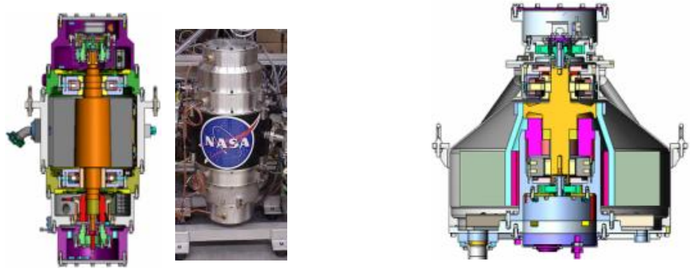






Dev 1 - 300 W-hr
4.1 W-hr/kg
Full Speed Once
USFS

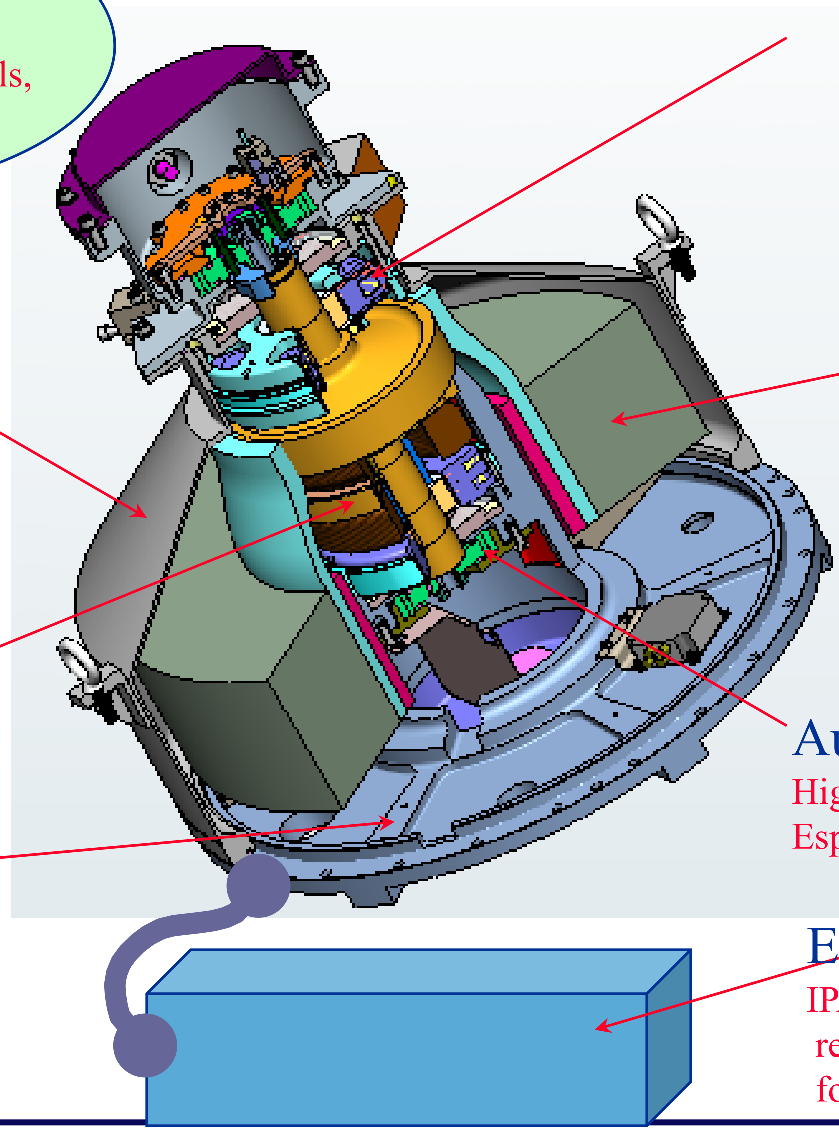
D1 - 330 W-hr
4.7 W-hr/kg
Full Speed Many Times
GRC/TAMU/USFS



G2 - 581 W-hr
6.1 W-hr/kg
Modular, Low Cost
GRC/TAMU

G3 - **2136** W-hr
35.5 W-hr/kg
High Energy, S.E., Life
GRC/TAMU/UT-CEM

Flywheel System

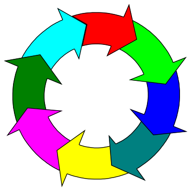


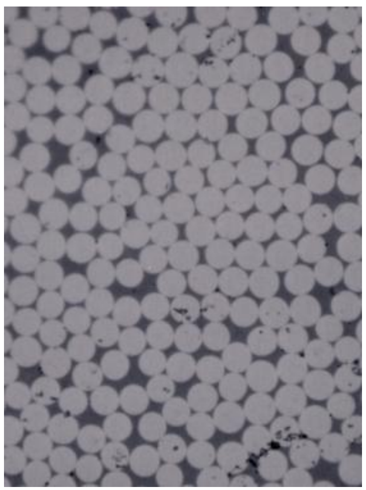
Flywheel Design and Topology

- Overview of Rim and Hub Types
- Flywheel Design Considerations
- Examples of Rim and Hub Types

Rim Types

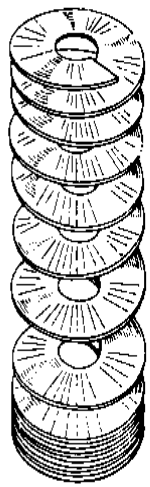
Filament Wound





- **Wet or Pre-preg**
- **High FVR (80%)**
- **Low Transverse (radial) Strength**

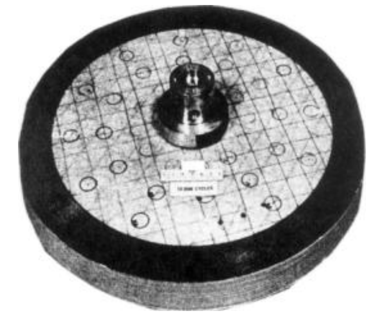
Polar Weave



Dow-UT/ AMT

- **Radial Reinforcement to increase Transverse Strength**
- **Kinks in Fibers Eliminate Advantages**

Laminated

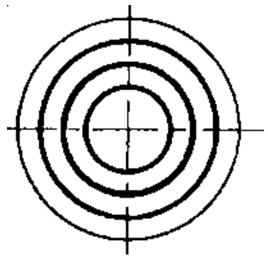


GE

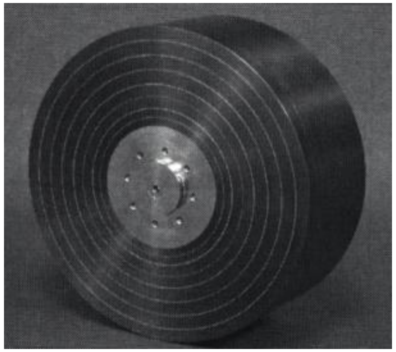
- **Final Two DOE Rotors of 80's**
- **Similar Benefits as Filament Wound**

Hub Types

Preloaded

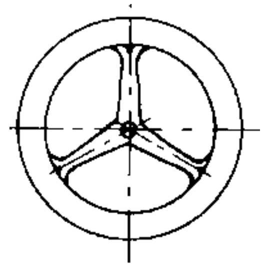


(g) multi-rim

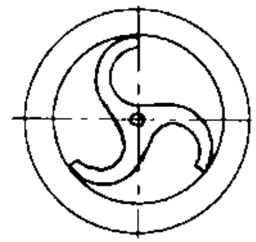


- Robust, Benign Failure Mode
- Lowest Specific Energy
- FESS Program

Growth matching



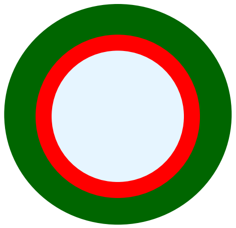
(e) multi-spoke

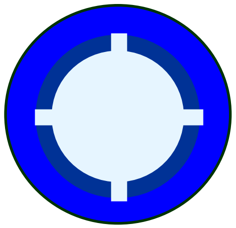


(a) curved spokes

- High Specific Energy
- Hub Does Not Influence Rim Stress State
- Composites Hubs Promise Longer Life over Metal Concepts

Mass Loaded

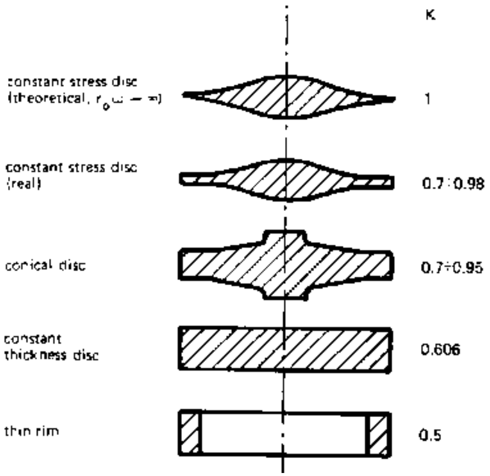




- High Specific Power
- Most compact design – esp. if magnets are embedded for MB & M/G
- Complex Failure Modes- Potentially Catastrophic

Why Composite Materials

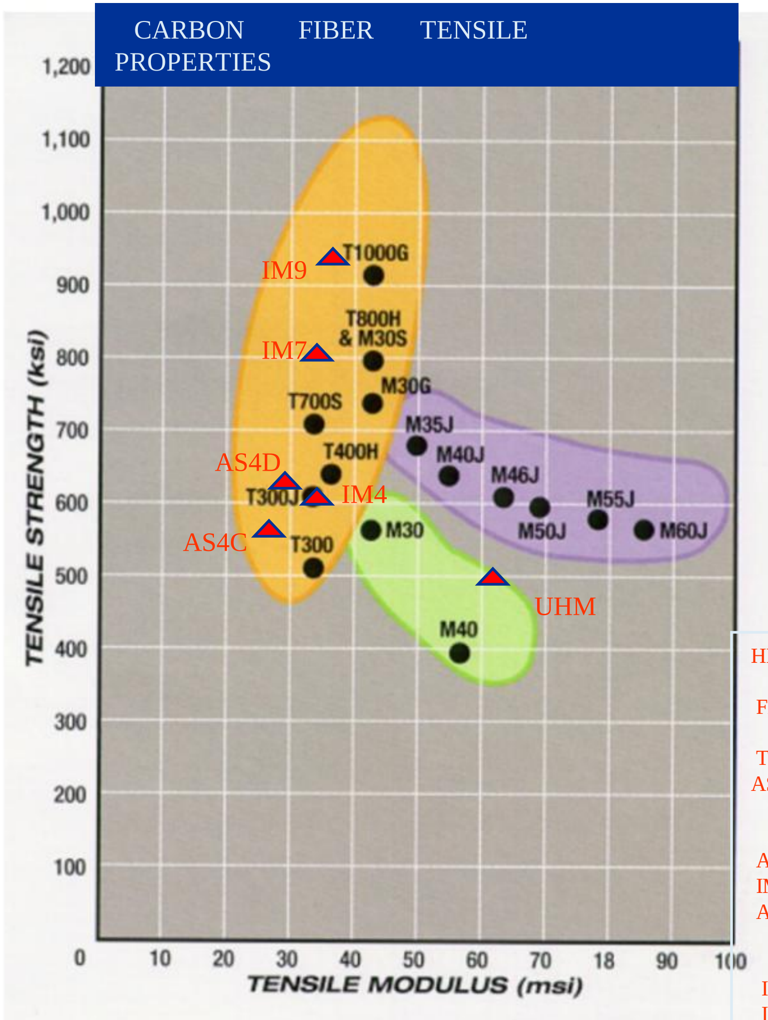
$$S.E. = K\frac{\sigma_u}{\rho}$$

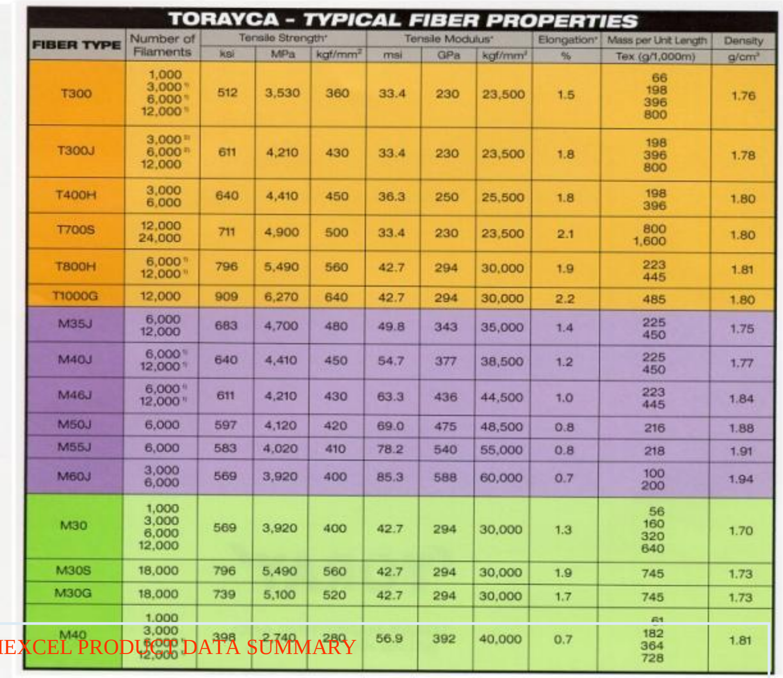


Material	S.E (Wh/lb)
Steel	25
S-glass	97
AS4C-carbon	97
T1000-carbon	162

- Use of composites allows flywheels to achieve a higher energy and power densities, but can also produce much more benign failure modes (radial delamination or outer ring burst) than do metals
- Using Higher strength materials allows smaller rotors, yet store same amount of energy because of larger tip speed; less momentum--increases SE and can reduce gyroscopic effects

CARBON FIBER TENSILE PROPERTIES





TORAYCA - TYPICAL FIBER PROPERTIES

FIBER TYPE	Number of Filaments	Tensile Strength* ksi	Tensile Strength* MPa	Tensile Strength* kgf/mm²	Tensile Modulus* msi	Tensile Modulus* GPa	Tensile Modulus* kgf/mm²	Elongation* %	Mass per Unit Length Tex (g/1,000m)	Density g/cm³
T300	1,000 3,000 6,000 12,000	512	3,530	360	33.4	230	23,500	1.5	66 198 396 800	1.76
T300J	3,000 6,000 12,000	611	4,210	430	33.4	230	23,500	1.8	198 396 800	1.78
T400H	3,000 6,000	640	4,410	450	36.3	250	25,500	1.8	198 396	1.80
T700S	12,000 24,000	711	4,900	500	33.4	230	23,500	2.1	800 1,600	1.80
T800H	6,000 12,000	796	5,490	560	42.7	294	30,000	1.9	223 445	1.81
T1000G	12,000	909	6,270	640	42.7	294	30,000	2.2	485	1.80
M35J	6,000 12,000	683	4,700	480	49.8	343	35,000	1.4	225 450	1.75
M40J	6,000 12,000	640	4,410	450	54.7	377	38,500	1.2	225 450	1.77
M46J	6,000 12,000	611	4,210	430	63.3	436	44,500	1.0	223 445	1.84
M50J	6,000	597	4,120	420	69.0	475	48,500	0.8	216	1.88
M55J	6,000	583	4,020	410	78.2	540	55,000	0.8	218	1.91
M60J	3,000 6,000	569	3,920	400	85.3	588	60,000	0.7	100 200	1.94
M30	1,000 3,000 6,000 12,000	569	3,920	400	42.7	294	30,000	1.3	56 160 320 640	1.70
M30S	18,000	796	5,490	560	42.7	294	30,000	1.9	745	1.73
M30G	18,000	739	5,100	520	42.7	294	30,000	1.7	745	1.73
M40	1,000 3,000 6,000 12,000	398	2,740	280	56.9	392	40,000	0.7	61 182 364 728	1.81

HEXCEL PRODUCT DATA SUMMARY

Fiber Type	Number of Filaments	Tensile Strength * KSI	Tensile Strength * Mpa	Tensile Modulus * MSI	Tensile Modulus * Gpa	Tensile Strain *	Weight/Length (g/m)	Density (g/cm3)
AS4C	3,000	560	3,860	33	226	1.7	0.200	1.77
	6,000	560	3,860	33	226	1.7	0.400	1.77
	12,000	560	3,860	33	226	1.7	0.800	1.77
AS4D	12,000	610	4,207	35	241	1.7	0.760	1.78
IM4	12,000	600	4,138	40	276	1.5	0.735	1.73
AS4	3,000	570	3,930	32	221	1.7	0.211	1.79
	6,000	570	3,930	32	221	1.7	0.425	1.79
	12,000	570	3,930	32	221	1.7	0.857	1.79
IM6	12,000	760	5,240	40	276	1.7	0.448	1.76
IM7	6,000	780	5,379	40	276	1.8	0.223	1.77
	12,000	780	5,379	40	276	1.8	0.446	1.77
IM8	12,000	790	5,447	44	303	1.7	0.448	1.80
IM9	12,000	920	6,343	42	290	2.0	0.331	1.79
UHM	3,000	500	3,447	64	441	0.8	0.086	1.87
	12,000	500	3,447	64	441	0.8	0.341	1.87

* Typical Lot Average Properties

* Tensile modulus calculated at secant 6000-1000

T1000G and IM9 2.1 and 2.0 %

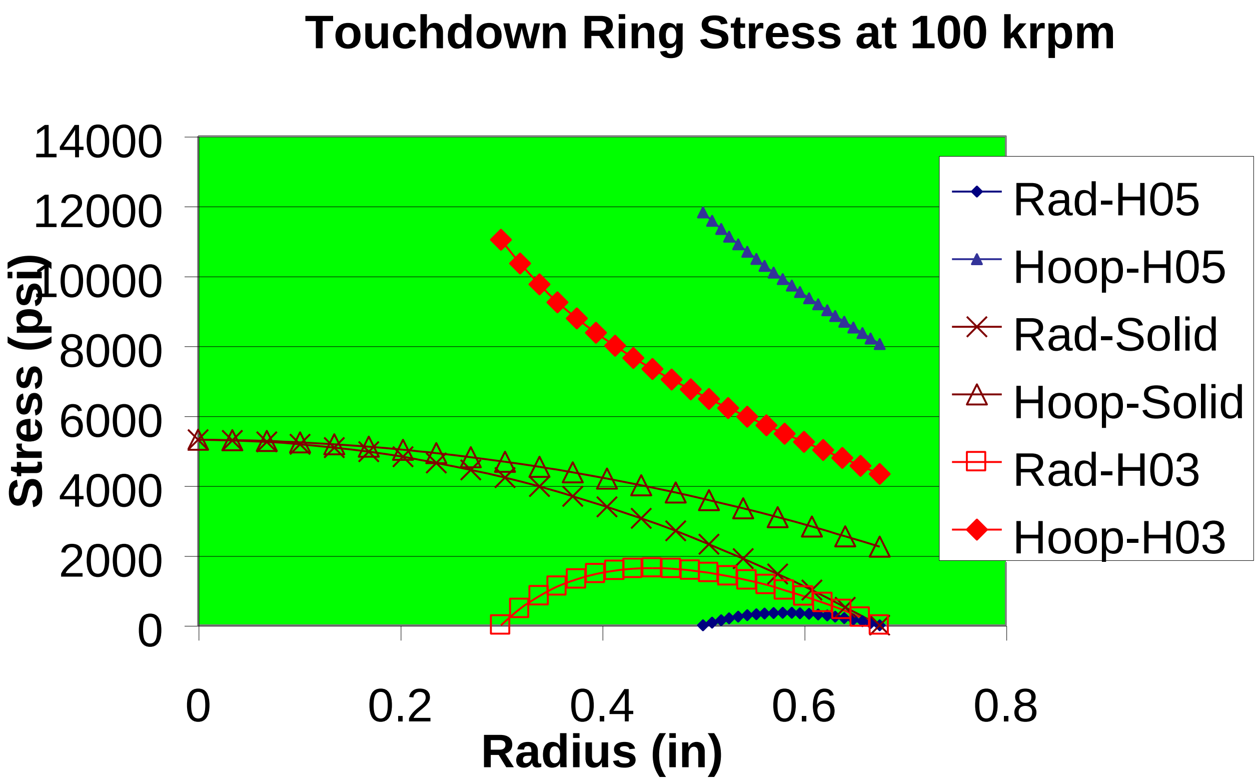
Flywheel Design Considerations

- Generally what is required for composite rotor designs is an accurate stress analysis and identification of limiting failure modes
- For given material, the rotor stresses, displacements, and interfacial pressures are expressible in terms of various design parameters:
  - mean radius, thickness, interference fits, material gradation, speed
- Stress Analysis must account for residual stresses, temperature, moisture, and time dependent material behavior

How is a flywheel constructed to operate safely?

- A rotating structure develops both hoop and radial stresses.
- The filament winding manufacturing process of composite flywheel rims results in orthotropic material properties such that the hoop stress is approximately two orders of magnitude higher than the radial stress.
- The hoop failure mode is the potentially catastrophic failure mechanism as the energy is released to the housing.
- Fortunately, composite fibers have excellent fatigue strengths in the longitudinal direction allowing composite rims to survive hundred of thousands of cycles.
- The radial failure mode results in the composite rim to be split into two rims, usually near the center where the peak radial stress occurs, resulting in an unbalance that is detectable.
- Mechanical fuse concepts that create an unbalance also exist to prevent premature hoop failures.
- Many other considerations are needed to ensure safe operation (containment for terrestrial applications) but no show stoppers

Metal Disks -Solid and Central Hole



Hole ~ 2X Solid

$$\sigma_r = \sigma_\vartheta = \frac{3+\upsilon}{8}\rho\,\omega^2 \left(b^2 - a^2\right)$$

$$\sigma_\vartheta(Max) = \frac{3+\upsilon}{4}\rho\,\omega^2 \left(b^2 + \frac{1-\upsilon}{3+\upsilon}a^2\right)$$

1-D Plane Stress – Orthotropic Materials

Centrifugal

$$\sigma_c = \rho\omega^2 r_o^{\,2}\,\frac{3+\nu_{cr}}{9-\mu^2}\left[\mu\, l\,\chi^{\mu-1} + \mu\left(-1\right)\chi^{-\mu-1} - \frac{\mu^2+3\nu_{cr}}{3+\nu_{cr}}\chi^2\right]$$

$$\sigma_r = \rho\omega^2 r_o^{\,2}\,\frac{3+\nu_{cr}}{9-\mu^2}\left[l\,\chi^{\mu-1} + \left(-1\right)\chi^{-\mu-1} - \chi^2\right]$$

$$where: \mu^2 = E_c / E_r$$

$$l = \left(\beta^{-\mu-1} - \beta^2\right) / \left(\beta^{-\mu-1} - \beta^{\mu-1}\right)$$

$$\beta = r_i / r_o \qquad \chi = r / r_o$$

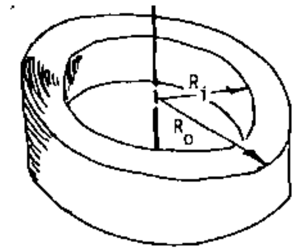
- Pressure: Internal & External

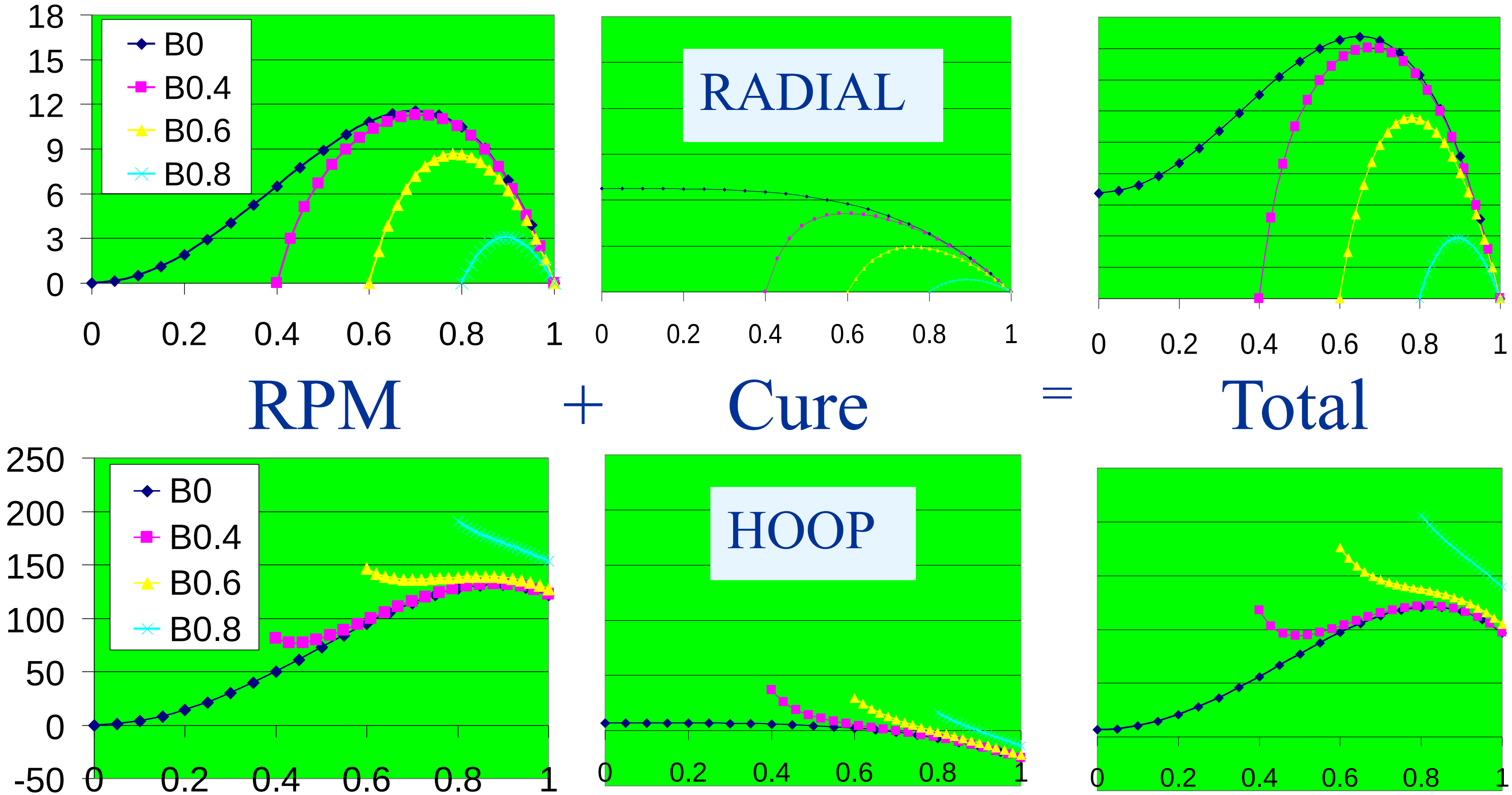
$$\sigma_c = \left(\frac{P\beta^{\mu+1} - Q}{1-\beta^{2\mu}}\right)\mu\,\chi^{\mu-1} + \left(\frac{P - Q\beta^{\mu-1}}{1-\beta^{2\mu}}\right)\mu\,\beta^{\mu+1}\chi^{-\mu-1}$$

$$\sigma_r = \left(\frac{P\beta^{\mu+1} - Q}{1-\beta^{2\mu}}\right)\chi^{\mu-1} + \left(\frac{P - Q\beta^{\mu-1}}{1-\beta^{2\mu}}\right)\beta^{\mu+1}\chi^{-\mu-1}$$

- Similar equations exist for Temperature and residual internal Moment

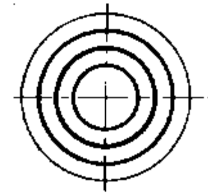
Single Ring RPM+Cure Stress



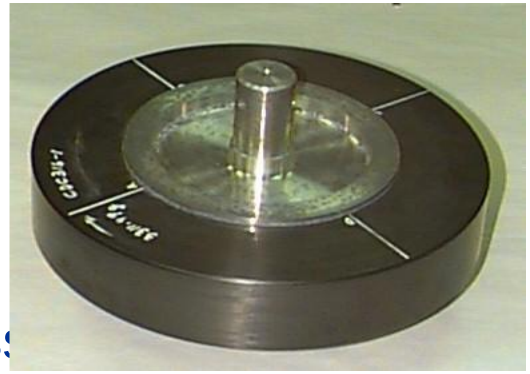


Hoop stress is typically 2 orders of magnitude larger than radial stress

Preloaded Designs–Single Rim

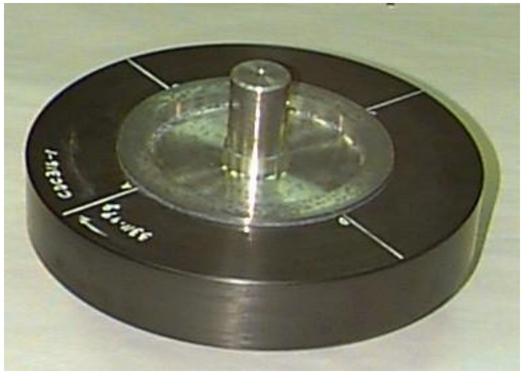


(g) multi-rim

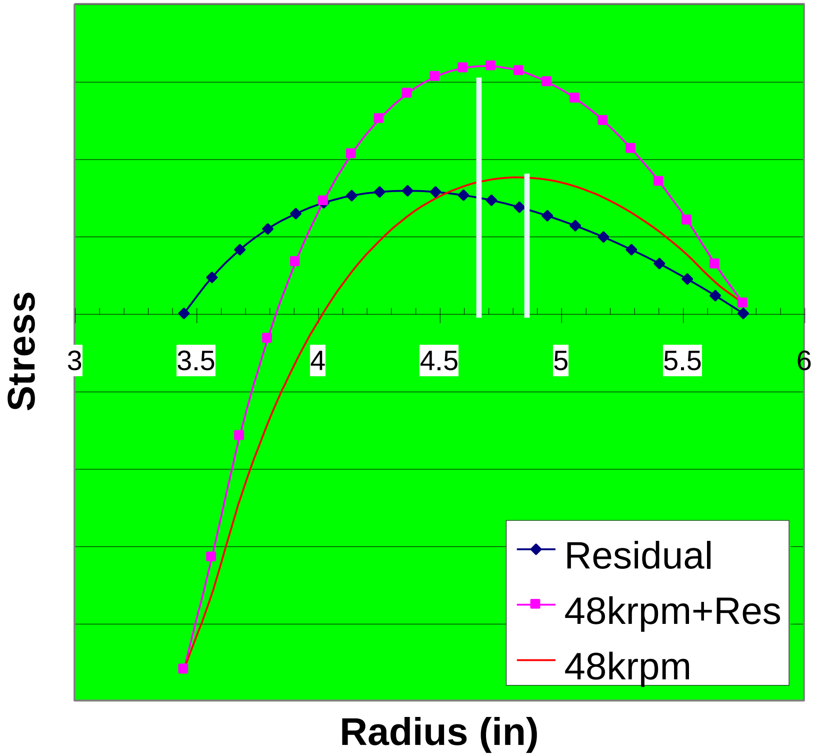


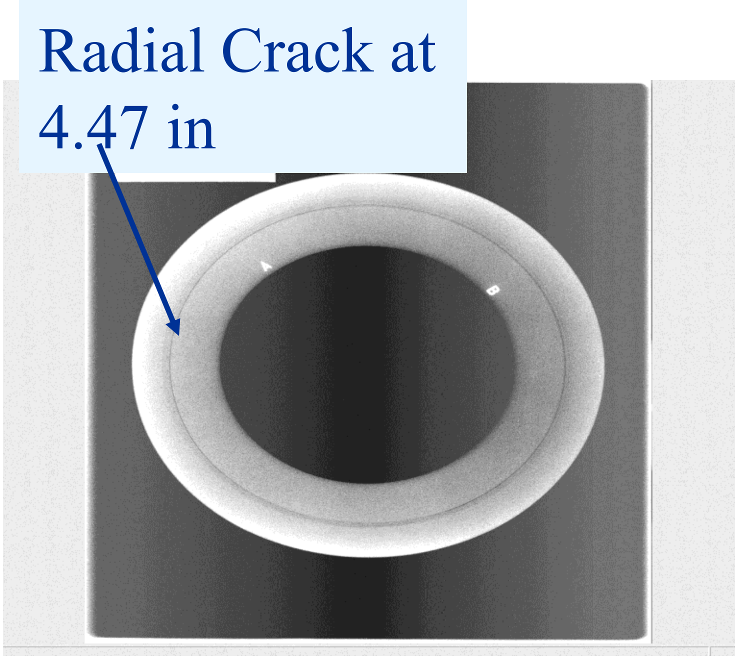
- “Pancake Designs”
- Single Ring Stress State
  - Centrifugal, Interference (Internal Press stages and tension), Temperature, Material Properties(Quality)
- Poor Transverse Strengths
- No long term fatigue data under **Biaxial** (tension-tension) state of stress

Pancake Rotor NDE/Stress



Effects of Preload, Centrifugal, and Residual Stress on Crack Location

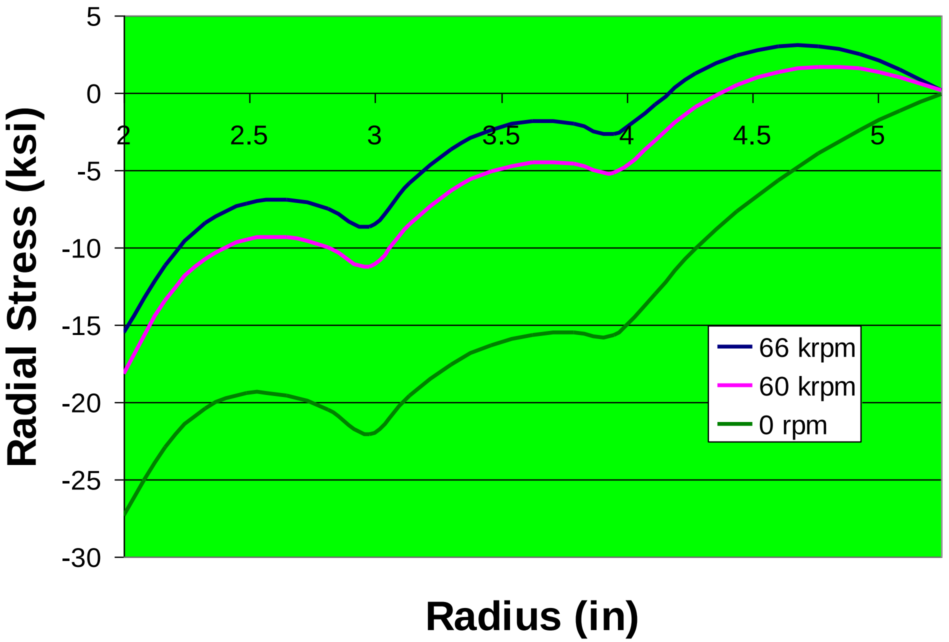




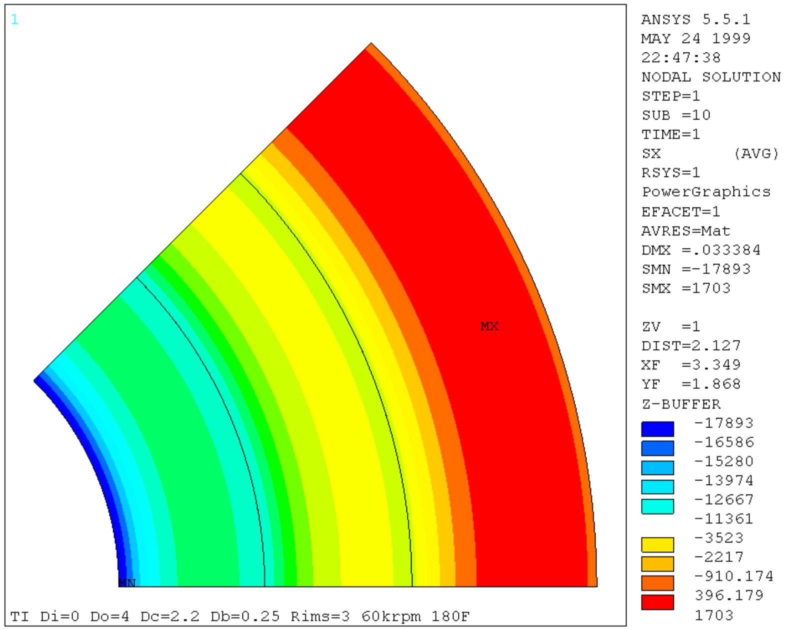
An est. residual would shift radial peak from ~4.8 to 4.67in
Else, need 12% ΔE to match – (no E test data avail, nor wind T)

Multi-Ring Stress Distribution*

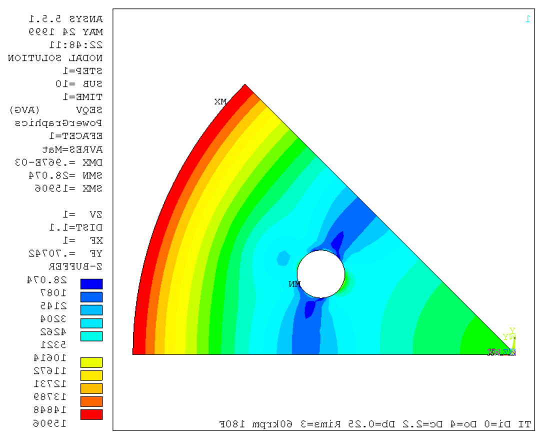
Ring Radial Stress vs Radius



Radial Stress Distribution @ 60 krpm



Hub Stresses Reduced by Press-Fit and Ring Stiffness



2D Planer Model

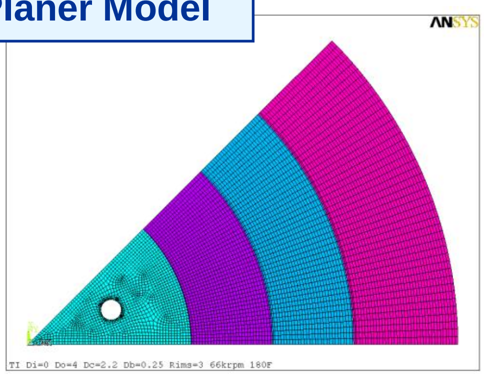
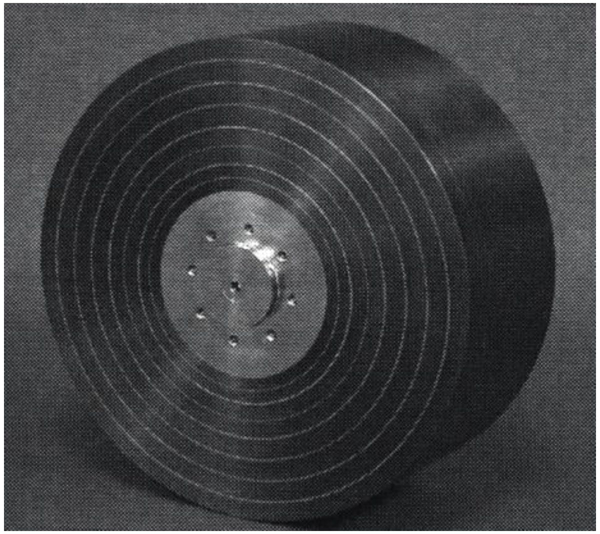
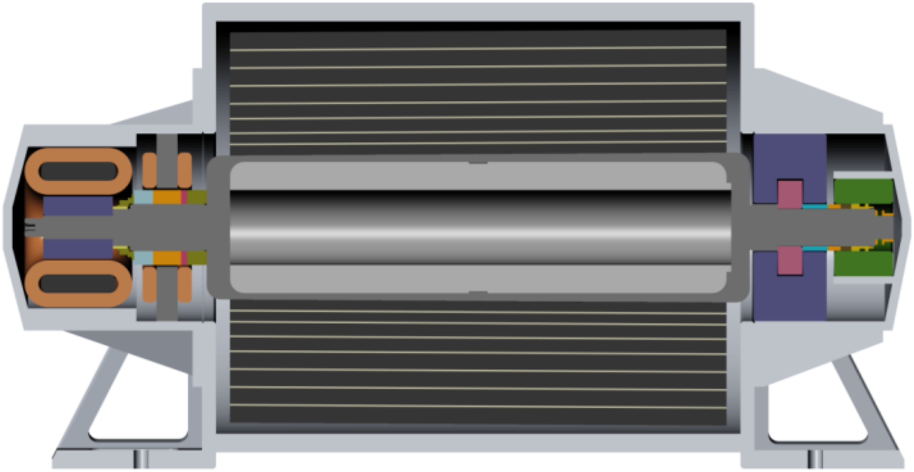


*Illustration Purposes Only
Non-Optimized Config

UTCEM Multi-Ring Press

- FESS Program Baseline
- 15+ years History



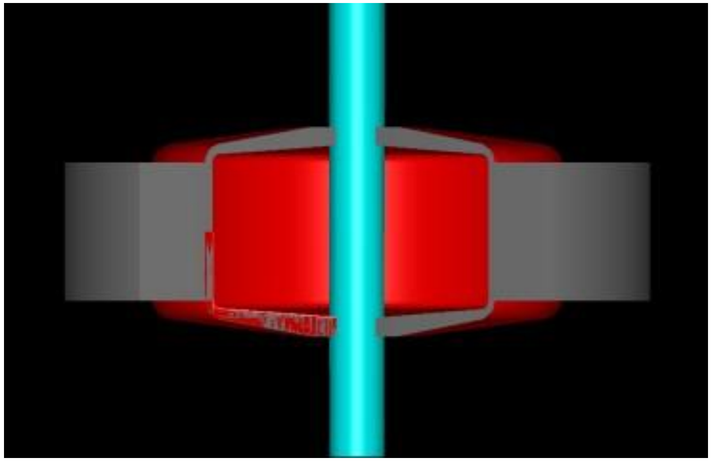


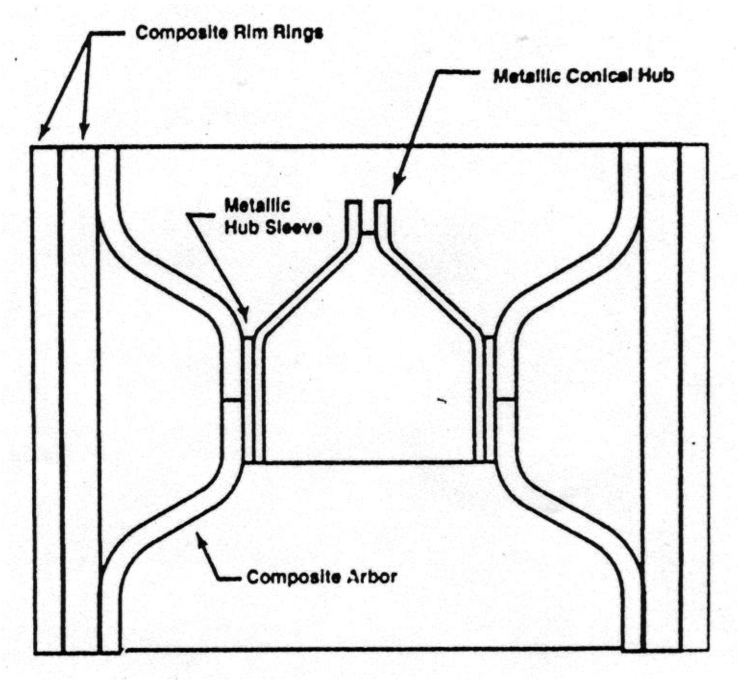
Multiring Advantages/Disadvangtages

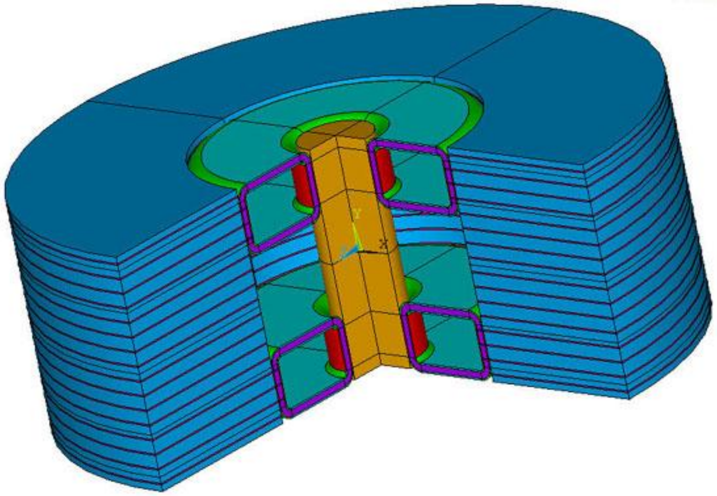
- Interference Fits maintain compressive radial stresses and arrests cracks
- Smaller Ri/Ro--thinner rings--reduces residual cure stresses
- Failure mode moved to outer ring allows limited failure or fail-safe design
- Allows design optimization--redistribution of stresses
- Allows smaller hub diameters to improve fatigue life
- Increases specific energy vs single ring
- Demonstrated tip speeds (>1300 m/s) and long history
- Fatigue > 300K cycles (15 yrs LEO)

- Multiple Press Fits have larger assembly and tooling costs
- Multiple Rings Pressed on shaft will have lower specific energy than “growth matching” or mass loaded designs
- Multi-ring rotors with elastomeric layers may introduce critical speeds within operational range
- potential for viscoelastic effects

Growth Matching--Flexible Composite Hub Designs





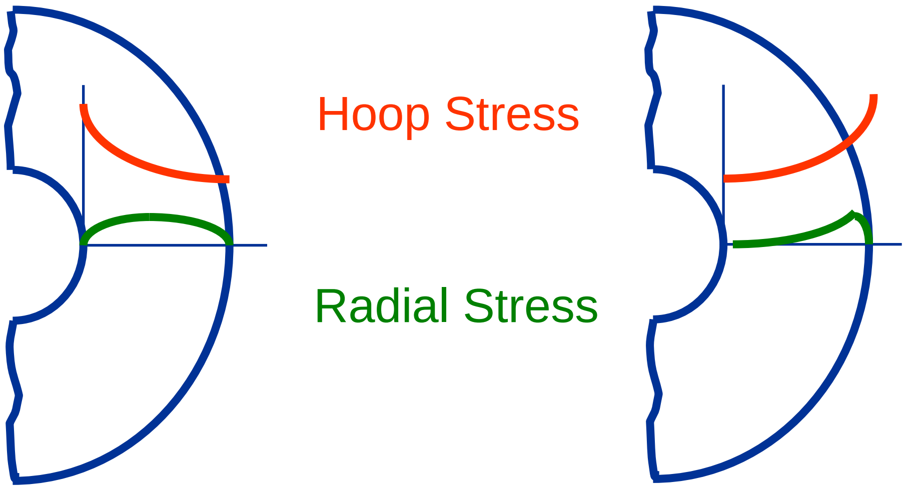


FESI (Canada)– Mark 4

- Growth Matching Aluminum Hub
- Mass-Loading Rim (S-Glass, Carbon)

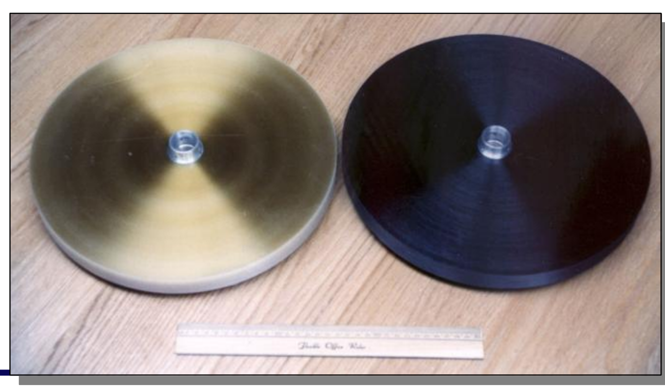
2000 AFRL “FACETS” Rim/HUB

Fail Safe Rotor Concept



Thick Epoxy Matrix Composite ($E_\theta/E_r \sim 10$)

Thick Elastomeric Matrix Composite ($E_\theta/E_r \sim 10^4$)



Rationale

Single disk construction

- simplified hub
- reduced mfg. cost

Potentially self-arresting failure mode

- highest stresses at outside radius

Rule = 1 ft (30.5 cm)

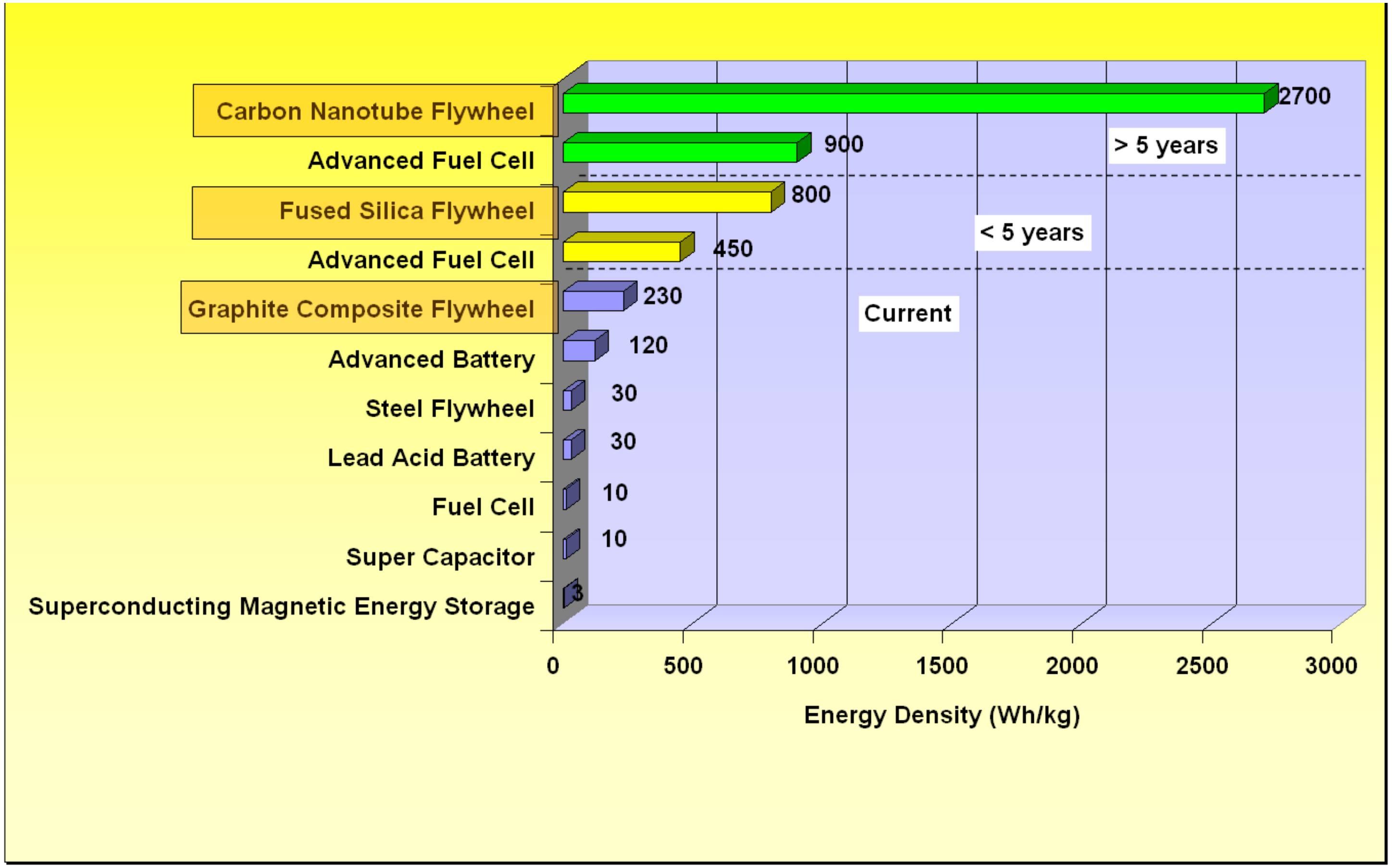
PENNSTATE 1855

Are Flywheels Safe?

- The simple answer is yes, that flywheels can be designed for safe operation either by a fail-safe or safe-life design process. In a fail-safe approach, containment ensures that any premature failure does not propagate to other systems. In space applications to save weight, the safe-life approach certifies the design will operate for up to four times its service life. Redundancy is implemented at the component level to ensure high reliability.

What Energy Density is Possible???

- Higher Energy Density Still Possible (translates to lower cost)
- Longest Energy Storage Life of 15 to 30 years
- Flywheels can handle a 200F Range without thermal control



Future R&D

- Advanced carbon materials
- High Speed bearings and motors
- Inside/Out Topology – A Thin Rotating Rim
- While development continues to double the 100 W-hr/kg at the rotor level or 50 W-hr/kg at the system level, achieving both high energy density at a low energy level (100-300 Whrs) still presents a significant technical challenge.

Flywheel Advantages

- Long life of 15 years
- High combined specific energy and power
- Large Temperature Range (-45ºC to +50ºC), minor performance impacts with increasing range, cold soak ok
- Known state of charge
- Fault Tolerant
- Built in diagnostics for health monitoring
- Can easily provide 10 times peaking power capability
- Fault Isolation can eliminate electronics (a motor and generator can isolate faults
- Can eliminate (most of) Attitude Control System on LEO satellites

Flywheels: A Key Technology for Renewable Energy Storage

- Intermittent energy sources such as solar and wind can use the power grid to absorb production at high penetration levels require grid energy storage
- Flywheels can store and release kinetic energy quickly over many charge-discharge cycles to provide frequency regulation support
- Technology development over the past decade have enabled flywheels to become a commercial product with many possible uses including trains, cranes, UPS
- With the aid of new technology to lower costs and increase stored energy, flywheels will play a significant role in securing global energy sustainability